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# A MODEL FOR WORK FUNCTION CHARACTERISTICS-BASED PRIORITIZATION OF TECHNOLOGIES FOR CAPITAL PROJECTS

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by

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To my wife

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# A MODEL FOR WORK FUNCTION CHARACTERISTICS-BASED PRIORITIZATION OF TECHNOLOGIES FOR CAPITAL PROJECTS

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Pragmatic construction professionals and the price-competition-oriented market inhibit the construction industry from investing in advanced technologies. The construction industry has taken advantage of new advanced technologies less frequently than other industries. However, owners, designers, and contractors have recently recognized that improving project performance and sustaining greater competitiveness are driving forces behind implementation of advanced technologies. At the same time, they have been questioning where and what they should implement first. An effective prioritization methodology helps the construction industry to increase the chance of successful investments in new technology development.

The objective of this study is to build a theoretical model for identifying research and development (R&D) investment opportunities exist with high value potential. The gap between measures of technology supply and demand is used to determine the relative priorities of future technology development. The relative demand for technologies is hypothesized to be closely associated with particular work functions.

This dissertation develops and tests a proof model to prove that work function characteristics can serve as an effective model for technology demand. To do so, a comprehensive list of work function characteristics is developed. After proving the value of the work function characteristics, this study applies the work function characteristics in determining the priorities for future technology R&D for capital facility projects.

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# CHAPTER 1 INTRODUCTION

## 1.1 Background

It is widely recognized that compared with other industries, the construction industry is hesitant to develop or adopt new technology and takes relatively less advantage of advanced technologies. Price competition market share, highly fragmented research and development (R&D) resources, minimal R&D investment, and a risk aversion attitude have often been offered as explanations (Anderson 1995). This hesitance becomes serious when we compare the U.S. construction industry with its international competitors in R&D investment. An investigation by the Center for Engineering Research Foundation (CERF) in1993 demonstrated that the five largest U.S. construction firms invested a total of $6.82 million on R&D out of total revenues of nearly $14 billion, which was just one-twentieth of the amount invested by their Japanese counterparts.

Recently however, owners, designers, and contractors have started to recognize that the implementation of advanced technologies contributes to the improvement of performance in construction projects (Mitropoulos and Tatum 1995). With this growing recognition of the potential benefits of advanced technology, researchers and industry professionals have been asked to determine prioritization of new technology development and adoption. From the technology user’s standpoint, prioritization is a matter of deciding which technology should be adopted or purchased first, and from the technology suppliers' point of view, it is a matter of where their resources should be allocated.

An example of R&D prioritization can be found in Johnston's critique on funding agencies in the U.S. (1995). Johnston insisted that funding agencies should put more emphasis on construction means and methods, pointing out that only 2.5% of civil engineering-related research was focused on construction means and methods. Based on a survey of 273 owner companies, Johnson and Clayton (1998) also invoked prioritization-related issues. When they surveyed the problems that the industry faces in implementing information technology, three of the top four problems were: measuring results, prioritizing technology, and evaluating return of investment; rather than reliability, cost, or familiarity of new technology. Paulson (1995) also critically noted that 90% of academic research efforts were focused on advanced technology that might benefit less than 10% of the world's needs. Moore (1999) also pointed out a gap between R&D and end-users in high-tech business.

While prior research has recognized an industry-wide need for R&D prioritization, research at the work function level can provide a more specific roadmap for determining R&D priorities. In determining priorities at the work function level, both users and suppliers have a substantial need for an effective method of assessing technology supply and demand in order to identify a gap between the two. In assessing technology demand, it is rational to expect that certain work function characteristics (WFCs) drive technology demand more than others and can be used to assess technology demand to a considerable degree. The benefit from assessing technology demand by characteristics of work functions (WFs) provides insight into the question of why certain technologies are used more than others, which conventional methods of prioritizing technology R&D, mainly focused on potential economic impact, do not provide. By complementing a WFCs-based analysis, therefore, future R&D roadmaps can be characterized according to an assessment of WFCs-based technology demand.

In spite of the potential use of WFCs, few studies have recognized the value of WFCs as technology demand drivers or utilized WFCs-based technology demand in prioritizing technology R&D. Another advantage of the study is that the proposed application model can produce R&D prioritization without a time-consuming supply assessment.

## 1.2 Research Objectives

After recognizing the necessity of technology R&D prioritization at the WF level, and the value of WFCs as technology demand factors, this study is centered on the following two main objectives:

1. Propose and test a proof model for using work function characteristics to gain insight into the demand for technology associated with individual work functions; and

2. Develop an application model for effectively prioritizing industry R&D needs by exploiting work function characteristics-based technology demand assessments.

The first main objective utilizes WFCs to guide an understanding of technology demand. Until now, no technical approach has been devised to relate WFCs to the technology demand of individual WFs. To devise an effective approach, an inclusive set of WFCs and a model incorporating technology demand should be compiled first. A model to assess the supply status of WFs is also required for a comparison with the demand status. In order to support the first objective, therefore, specific sub-objectives were developed as follows:

- Understand the degrees of technology use at the WF level,
- Develop a comprehensive list of WFCs that are applied to WFs in capital facility projects,
- Develop a model to assess technology demand based on WFCs, and
- Develop a model to assess technology supply in general.

The second main objective can be accomplished after WFCs are proven to be technology demand drivers. Knowledge of technology use and the technology demand assessed by WFCs are the main components of the application model. The application model can produce R&D prioritization without the supply model, which is a time-consuming process requiring considerable efforts. The model also requires explicit relationships among technology use, technology supply and demand, and the gap between the supply and demand. These relationships are expressed by the research assumptions presented in the following section.

The purpose of WFC-based analysis is to develop an analysis approach that would complement conventional methods.

## 1.3 Research Hypothesis and Assumptions

This section addresses the research hypothesis to be tested and the four assumptions involved in developing the theoretical model. The first objective of the research is to determine whether WFCs can explain the variance of technology demand at the WF level to a substantial degree. A research hypothesis is set to test this plausible idea.

**Hypothesis**: *The relative demand for technology at the WF level is largely a function of WFCs.*

Several assumptions were established before developing the research proof model and the application model. These assumptions are within common reason and can be applied to the theoretical model without any proof processes.

The first assumption establishes an explicit relationship among technology use, technology demand, and technology supply:

Assumption 1: The maximum level of technology use is approximated by the minimum level of either technology demand or technology supply.

This assumption is logical because the level of use cannot usually exceed the level of supply, and few corporate or professional entities in the design and construction industry adopt technology without a strong demand. Therefore, the level of technology use can be measured by the minimum level of either technology demand or technology supply.

Table 1-1 explains all the possible combinations of Assumption #1 with three-scaled ordinal variables.

**Table 1-1: Base Assumption for Technology Use**

| IF | AND | | THEN |
|---|---|---|---|
| Technology Demand | Technology Supply | | Technology Use |
| High | High | | High |
| High | Medium | | Medium |
| High | Low | | Low |
| Medium | High | | Medium |
| Medium | Medium | | Medium |
| Medium | Low | | Low |
| Low | High | | Low |
| Low | Medium | | Low |
| Low | Low | | Low |

An additional assumption can be derived from the base assumption by applying rules of logic. This derived assumption enables one to deduce demand or supply values, given a particular level of the technology use. For example, if a technology use level is lower than a demand level, a supply level is charged of lowering the level of technology use. Therefore, the supply level can be approximated by the technology use level. Note, however, that the combinations of values produce three impossible and two undetermined relationships, which make Assumption #2 less useful than Assumption #1.

Assumption 2: Knowledge of both technology demand (supply) and technology use can be used as a surrogate for the technology supply (demand) variable (Table 1-2).

**Table 1-2: Derived Assumption for Surrogate of Technology Supply and Demand**

| IF | AND | | THEN |
|---|---|---|---|
| Technology Demand (Technology Supply) | Technology Use | | Technology Supply (Technology Demand) |
| High | High | | High |
| High | Medium | | Medium |
| High | Low | | Low |
| Medium | High | | Impossible |
| Medium | Medium | | High/Medium |
| Medium | Low | | Low |
| Low | High | | Impossible |
| Low | Medium | | Impossible |
| Low | Low | | High/Medium/Low |

The third assumption establishes the magnitude of gap size, and the fourth suggests R&D priority. A gap is found where supply does not meet demand. The magnitude of the gap size can be approximated by subtracting a supply value from a demand value. The R&D priority is assumed to be determined by the size of the gap between technology supply and demand. The larger the gap found, the higher the priority.

Assumption #3: The difference between technology supply and demand can be used to assess the size of gap in technology supply and demand (Table 1-3)

Assumption #4: The gap between technology supply and demand can be used to assess R&D prioritization (Table 1-4).

**Table 1-3: Assumption for the Gap between Supply and Demand**

| IF | AND | | THEN |
|---|---|---|---|
| Technology Demand | Technology Supply | | Gap |
| High | High | | Small |
| High | Medium | | Medium |
| High | Low | | Large |
| Medium | High | | None |
| Medium | Medium | | Small |
| Medium | Low | | Medium |
| Low | High | | None |
| Low | Medium | | None |
| Low | Low | | Small |

**Table 1-4: Assumption for R&D Prioritization from the Gap**

| IF | | THEN |
|---|---|---|
| Gap | | R&D Prioritization |
| Large | | High |
| Medium | | Medium |
| Small | | Low |
| None | | None |

Figure 1-1 illustrates the relationships among the research assumptions and main components. All the investigations of technology supply and demand, and following gap analysis are performed at the WF level. As stated in Assumption #1, technology use is a function of technology supply and demand. Technology demand is assumed to be a function of WFCs associated with the potential benefits of added technology. Technology supply can be subdivided into three components: tools, base technologies, and interface standards. A full description of this supply model is presented in Chapter 6. A "gap" is obtained by subtracting technology supply level from technology demand level (Assumption #3). R&D prioritization is a direct function of the gap size between supply and demand (Assumption #4).

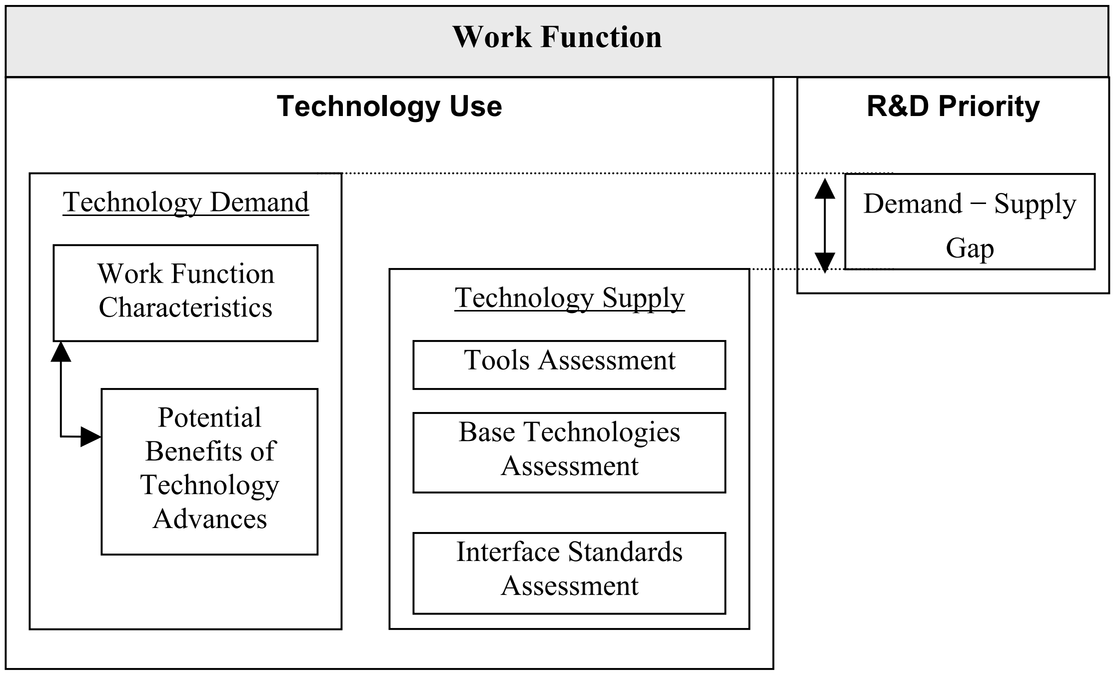



**Figure 1-1: Illustration of Research Assumptions and Main Components**

## 1.4 Research Scope and Limitations

Technologies and tools applied to capital facility projects are tremendously diverse. The scope of this study encompasses technologies associated with 68 common work functions of capital facility projects, selected by a prior research team at the University of Texas at Austin. Survey results of integration and automation (IA) metrics obtained from the same research team are used to represent levels of technology use at the WF level.

All the models developed in the study, and the prioritization of R&D are assessed at the project-based WF level rather than the organization- or specific task-levels.

## 1.5 Dissertation Organization

This dissertation is composed of a total of eight chapters. Chapter 1 introduces the research background, the research objectives, the research hypothesis to be tested, a set of assumptions, the research scope and limitations, and the structure of this dissertation.

Comprehensive literature surveys conducted in order to understand current technology aspects of capital facility projects are presented in Chapter 2. Topics include suggested strategies for advanced technology adoption and transfer, impediments pointed out by professionals, technology supply and demand factors, limited survey results of current status technology supply including construction robotics, gap recognition between supply and demand, and survey results of technology use.

Chapter 3 details research methodology including research steps, research main components, data collection methodology, and statistical analysis applied to the collected datasets.

Chapter 4 provides statistical analyses of technology use. The analyses are aimed to provide a deeper insight into the levels of technology use at the WF level.

In Chapter 5, the complete process of WFCs development and data collection results and analyses of WFCs as technology demand driver factors are described.

Chapter 6 presents research proof process. The chapter includes the development of technology supply and demand models and hypothesis test based on survey results.

After proving the research hypothesis, Chapter 7 presents the application process. An application model, data collection, and analysis results are provided.

Finally, Chapter 8 concludes the study and recommends directions for future research.

# CHAPTER 2 TECHNOLOGY ASPECTS OF CAPITAL FACILITY PROJECTS

## 2.1 Introduction

Understanding the technology aspects of capital facility projects is crucial prior to developing any framework for the prioritization of technology R&D. Furthermore, an attempt to assess technology demand by means of WFCs requires a full grasp of the characteristics of technology supply and demand that are unique to the construction industry.

This chapter summarizes comprehensive literature surveys on the technology aspects that will be utilized in developing the research theoretical model. They include technology strategies at the industry or corporate level, recognized factors in making decisions about new technology adoption and evaluation, commonly known impediments, benefits from advanced technology as demand factors, supply factors and current supply status, the gap between supply and demand, and several investigations on technology usage.

## 2.2 Factors affecting Technology Strategies in the Construction Industry

In their six case investigations, Laborde and Sanvido (1994) revealed that company size and breadth of innovation, i.e., project-specific and company-wide innovation, are the factors that influence the innovation process. A large company has the ability to spread out risk over a large number of projects and provide extensive support to the R&D department. On the other hand, a small company suffers relatively less from bureaucracy and long communication channels. In terms of the breadth of innovation, the authors insisted that a company-wide approach to innovation should be more effective than project-specific innovation because formal departments can invest in broad areas on a long-term timeline with less schedule and cost constraints.

A couple of researchers pointed out missing components in establishing technology strategy in the construction industry. Anderson (1995) pointed out a lack of technology information depositories, and Cahoon (1995) underscored a lack of clear procedures on how to implement and evaluate new technologies.

A number of studies commonly emphasized an incentive system as an indispensable element of technology strategy. It includes recognition or reward to individuals within an organization, and benefit and risk sharing among intra-organizations (Tatum 1991, Ahmad 1991, Uwakweh 1991, Anderson 1995, Cahoon 1995, and Laborde and Sanvido 1994). For a systematic approach among organizations, contract documents should include incentives for advanced technology and responsible parties should share potential risks.

### ***Factors for New Technology Evaluation and Adoption***

The decision to adopt a new technology is the most critical procedure in implementing technology strategy. This decision is difficult because a decision maker should consider both tangible and intangible benefits and impediments. A couple of studies proposed a systemic procedure or a decision support tool for adopting advanced technology. This section mainly focuses on the factors applied in developing such a tool rather than evaluation technology.

Skibniewski and Chao (1992) proposed an evaluation methodology for advanced construction technology adoption using the analytical hierarchical process (AHP) method. The overall assessment consists of cost factors and benefit factors. The cost factors include net present worth from initial investment and operating costs and risk concerns regarding safety, system flexibility, and system reliability. The benefit factors involve competitive edge, quality performance, and schedule performance. Later on, they (1995) applied the same factors to a neural network-based approach for predicting the acceptability of a new construction technology.

Abdul-Malak et al. (1995) proposed a decision support system framework to enable highway contractors to evaluate the feasibility of adopting advanced construction technology. The system evaluates technology demand factors and impediment factors. The demand factors include competitive advantage from cost, quality, and schedule performance; technical benefits for problem solution; and productivity gain in labor skills. The impediment factors involve competitive market conditions, governmental constraints, contractor's financial constraints, human resources for new technology, and project constraints such as site conditions and specifications. It demonstrated that in cases where more weight is placed on financial considerations, the decision would favor an old technology.

## 2.3 Demand for New Technologies

In spite of several impediments, there exits driving forces for the development and adoption of new technologies. These driving forces are regarded as technology demand factors.

Abdul-Malak et al. (1995) identified three main technology demand factors: (1) competitive advantage including cost reduction, quality improvement, and schedule performance, (2) technical benefit gained from problem solution, and (3) vanishing skilled labor forces.

Mitropoulos and Tatum (1999) added one more factor, that of external requirements, to the above these three factors. External requirements are a specific technology demand by clients, regulators, or other project participants. In the study, they also measured the sensitivity of reaction by general contractors. The study insisted that contractors are more likely to adopt a technology on the basis of the external demands.

### ***Competitive Benefits***

Among the demand factors, competitive benefits are still the most appealing factor to potential users. Tatum (1991) claimed that the effective use of new technology could increase competitive advantage for both engineering and construction firms. These advantages include capability for technically challenging projects, cost and time saving for both builder and owner by operations improvement, and reputation as a technically progressive company.

Several researchers attempted to identify specific benefits from advanced technology as technology demand factors. Hampson and Tatum (1997) investigated the relationship between the level of technology strategy and the company's competitive performance. In this study, the authors found that the higher the levels of technology strategy employed, particularly in competitive positioning, depth of technology strategy, and organization fit, the better the competitive performance achieved from both market share and contract awards.

### ***Economic Benefits***

Chapman (2000), in a study of cost and benefit analysis of integration and automation technologies in industrial facilities, demonstrated that the use of FIAPP (Fully Integrated and Automated Project Processes) products and services would generate in excess of $2.0 billion (measured in 1997 present value dollars) cost savings to industrial facility owners and managers, and to contractors. These cost savings were broken down into: 1) lower first costs, 2) lower maintenance and repair costs, 3) fewer construction-related accidents, 4) reductions in delivery time, and 5) higher net income.

Researchers who developed construction robotics demonstrated the economic benefit of telerobotic or autonomous equipment from the fact that robotics could remove workers from hazardous work space. Lee et al. (1999) claimed the economic benefit of their robotic trenching and pipe installation system over a traditional workers-involved methodology. Similarly, Gregory and Kangari evaluated the cost and benefits in using teleoperated and autonomous systems to remediate unexploded ordnance and hazardous waste. They developed a new scenario based evaluation system, which considered interrelated operational variables simultaneously.

***Demand for IT***

Recently, information technology (IT) was recognized as one of the most potential fields applicable to the construction industry. Researchers and suppliers put a great deal of emphasis on technology demand applicable to capital facility projects. In applying IT, Ahmad et al. (1995) identified the dynamic nature of the construction process and the rapid change of business environment as driving forces. A large number of project participants from various organizations and fragmented project phases can obtain a tremendous technical advantage from efficient communication tools and integrated data resource sharing system.

Brandon et al. (1998) and Henry (1994) also stated opportunities for IT support in construction design and production. These included visualization, intelligence systems, and communications as well as information integration during the all phases.

Back and Moreau (2000) measured the cost and schedule performance enhancement in design related activities from aggressive information management strategies, resulting in 2-3% reduction in overall labor cost and 10% schedule performance improvement. Similar results were shown for materials management related activities. Additionally, a survey on the impact of IT from the owner's perspective (Johnson and Clayton 1998) indicated that IT could provide very positive impacts on collaboration among dispersed team members, inventory management, and overall labor productivity.

The Port Authority of New York and New Jersey (Zipf 2000) reported productivity enhancement from the technology incorporated project control process. The enhanced control process included the following technologies: LANs and WANs, an on-line project management manual, a project management integrated system, ERP, EDMS, and GIS incorporated with proper training for staff and total quality management.

Another recent research of the impacts of Design/Information Technology (D/IT) on building and industrial projects (Thomas et al. 2001) showed a positive correlation between the uses of D/IT and project performance. The study found that owners experienced project cost savings of 2.1 percent, and contractors experienced savings of 1.8 percent as D/IT use increased.

### ***Demand for Robotics***

In addition to the opportunities stimulated by IT, automated and robotized operations invite further potential for advanced technology demand (Henry 1994). Commonly anticipated benefits of replacing human workers with robotics include the following:

- Productivity enhancement particularly in high volume and repeated activities.
- Higher quality from precise machine control and less variation by worker's experiences.
- Stable project control from less dependency on labor market.
- Increased safety performance by eliminating workers from dangerous work environment.

Tucker et al. (1990) developed a methodology for identifying higher automation opportunities. The methodology identified 17 WFCs under five categories as a part of the automation opportunity evaluation (Table 2-1).

**Table 2-1: Concern Factors in Assessing Automation Opportunities (Tucker et al. 1990)**

| Concern | Concern factors |
|---|---|
| Safety | Hazardous to health<br>Physically dangerous<br>Elevated work<br>Polluted work space |
| Productivity | Repetitive<br>Sequential/Cyclic<br>Dirty/Unpleasant work<br>Weather impacts |
| Quality | Tolerance levels<br>Consistency / Repeatability |
| Worker Utilization | Requires specialized skills<br>More than one person needed<br>Tedious/Boring / Exhaustive |
| Super Human Handling | Meticulous work<br>Heavy lifts<br>High lifts<br>Physically exhaustive |

## 2.4 Technology Supply

Technology supply is not a single parameter. Rather it is included in every step from the conceptualization of an innovative idea to the commercialization of a product. Technology supply activities can include research on base technology development, technology adoption from other industry, and diffusion and transfer of available technology. One of critical functions in technology transfer is to assess a new technology by a reliable organization in a timely manner; thereafter, users can apply the new technology to their project, confirming codes and specifications. These supply activities are important as much as technology demand factors for the process of construction project innovation

While most professionals highlighted technology demand as driving forces to construction innovation (Cahoon 1995 and Anderson 1995), Nam (1992) pointed out that innovative technology was not necessarily demanded by owners, nor oriented to problem-solving situations. Instead, from ten innovative construction projects he inferred that technology supply-side factors played a significant role in the process of construction innovation. These supply-side factors acting as a technology push include: gathering already-known ideas as major sources, developing earlier technologies, and integrating R&D efforts.

***Current Status of Technology Supply***

In 1994, Aouad and Price compared construction planning and information technology supply between the U.K. and U.S. They found that critical path methodology (CPM) and bar chart technologies are the most dominant technologies in both countries. However, they also revealed some lacking areas of technology supply in the IT application. The authors found that the complexity of site conditions cannot be handled by presently available databases and the industry is not in favor of using expert systems and simulation techniques because of the large amounts of data input, lack of flexibility, and high cost. Additionally, the study showed the following technical problems in current IT supply.

- Lack of integrated computer programs.
- Lack of interface standardization.
- Lack of equipment compatibility.

In 1996, an exploratory survey of 273 architecture and engineer (A/E) clients, i.e. owner companies, was performed regarding the influence of information technology (Johnson and Clayton 1998). The survey ranked useful current and future information technologies, as shown in Table 2-2. In both fields, e-mail is ranked on top. Project management and scheduling software and wireless communication were expected to become increasingly useful in the next five years from the time of the survey execution.

**Table 2-2: "Very Useful" IT current and in Five Years (Johnson and Clayton 1998)**

| | IT "currently" very useful | | IT more useful "in the next 5 years" |
|---|---|---|---|
| (1) | E-mail | (1) | E-mail |
| (2) | Computer-aided design | (2) | Computer-aided facility management |
| (3) | Share files with e-mail attachments | (3) | Project management and scheduling software |
| (4) | Computer-aided facility management | (4) | Computer-aided design |
| (5) | CAD standards/layering | (5) | Shared databases |
| (6) | Shared databases | (6) | Wireless communication |
| (7) | Project management and scheduling software | (7) | CAD standards/layering |
| (8) | Electronic data interchange | (8) | Intelligent buildings |
| (9) | Intelligent buildings | (9) | Electronic data interchange |
| (10) | Wireless communication | (10) | Share files with e-mail attachments |

***Robotics in the Construction industry***

The most advanced technology supplied for physical resource related work functions is robotics. This section hopes to identify current supply status, actual benefits, and characteristics of the top-level supply.

Robotic systems have become commonly used in the manufacturing industry because they provide robust quality control, fewer constraints on working time, better process control, and a safer work environment. Combining all of these benefits, robots enhance productivity tremendously in spite of the high initial investment cost. Anticipating similar impacts on job sites, the construction industry recently started to develop and even implement robotic systems.

Japan is the leading country in implementing robotic systems in the construction industry. According to one survey on robotics in building industry

(Warszawski and Navon 1998), 75% of the total replies from eight countries came from Japan. This number is close to the actual portion of implementation dominated by Japan. While U.S. general contractors (GCs) generally do not have sizable R&D operations, Japanese large general contractors are committed to R&D as both a means to their short-term profitability, and their long-term growth strategy (Webster 1997).

The Development of robotics involves two different trends: single-task robotics and construction automation systems. Table 2-3 lists examples of single-task robots classified by functions developed in the U.S. and Japan. While it is true that most robotics research focuses on developing single-task robots, Japanese large contractors, in the 1990s, put greater emphasis on construction automation systems than on single-task robots (Higgins and Slaughter 1993). Table 2-4 presents a complete list of the construction automation systems used in Japan.

In the construction industry, economic gains from single-task robots, such as reduced cost and shortened construction time, have not met the initial expectations (Cousineau and Miura 1997). This disappointing finding was mostly explained by the additional efforts and time required during construction site preparation and clean-up phase after operation. Characteristics of construction projects that are different and sometimes opposite to those of assembly line procedures in the manufacturing industry can explain the difficulties in achieving anticipated benefits. The uniqueness of each project demands variation in robotic systems. Robotics must also cope with harsh environmental changes such as temperature, humidity, wind gusts, and dust. The need for extensive mobility and heavy-duty handling combined with the capability to sense surroundings presents another challenge in implementing robotics on job sites. However, it should be noticed that the robotic systems that have been employed significantly contributed to better, safer and cleaner job site environments compared to conventional sites (Cousineau and Miura 1997).

**Table 2-3: Work Functions Automated by Single Task Robotics (Cousineau and Miura 1997, Higgins and Slaughter 1993)**

| | | |
|---|---|---|
| Surveying or inspecting | Underground | |
| | Road and sidewalk | |
| | Underwater | |
| Excavating and Grading | Underwater | Leveling |
| | Rock | Drilling |
| | Open field | Grading |
| | Tunnel | Digging |
| Structure | Concrete | Form work<br>Rebar work<br>Concrete work –pouring, vibrating, screeding, finishing, water removing |
| | Steel | Erection<br>Framing or clamping<br>Fireproofing |
| Finish | Exterior | Painting<br>Tile installation<br>Pre-cast panel installation<br>Glazing |
| | Interior | Floor<br>Wall<br>Ceiling |
| Maintenance | Inspection | Tile<br>Clean room<br>Pipe |
| | Cleaning | Windows |
| | Repair | Concrete |
| Demolition | Demolition | Concrete |
| Miscellaneous | Underground detection | |
| | Level maker | |
| | Concrete block installation | |

**Table 2-4: Construction Automation Systems in Japan**

| System | Company | Year | Type |
|---|---|---|---|
| Push-Up | Takenaka | 1989-91<br>1993-95 | Office<br>Office |
| SMART System | Shimizu | 1991-94<br>1994-97 | Office<br>Office |
| ABCSystem | Obayashi | 1991-94 | Office |
| T-Up | Taisei | 1992-94 | Office |
| MCCS | Maeda | 1992-94<br>1995-98 | Office<br>Office |
| Akatsuki 21 | Fujita | 1994-96 | Office |
| AMURAD | Kajima | 1995-97 | Residential |
| Big Canopy | Obayashi | 1995-98 | Residential |

***Government Agency as a Technology Supplier***

Government agencies play a role as both technology demander and supplier. As a demander, government agencies are the major ordering organizations and their operation and maintenance activities involve tremendous amounts of technology demand. Public agencies purchase technology directly from suppliers, or demands industry entities to adopt a certain technology such as on-line submission of contract documents or CAD based drawing production.

The role of government agencies, however, should be underscored as a technology supplier. The role of government agencies have been less positive than they could be, relative to both the industry's potential capabilities and the nation's welfare (NRC 1992). The 1992 NRC report presented primary reasons why government agency at all the different levels should play a greater role in fostering new building technology:

- To achieve better cost, quality, and performance in government facilities themselves.
- To enhance the quality of life in the U.S. through encouraging better cost - initial or lifecycle, and performance in private sector building.
- To enhance U.S. industrial competitiveness in international market.

R&D funding, policies, regulations, and attitudes toward new technology are major factors affecting technology supply, particularly technology transfer and diffusion activities. However, with respect to building technology, the report argues that there is no U.S. government agency with explicit responsibility for representing or encouraging the enhancement of the nation's construction industry as a whole. Industry professionals frequently criticize adverse legal systems and regulatory constraints. Halpin (1990) stated the following factors restricting better performance in AEC research and development in the U.S.:

- Less technological competition in design due to stipulated-sum competitive-bidding system
- Lack of patent incentives
- Contract policies rewarding mediocrity
- Restrictive and lagging building codes for new technologies
- Liability issues from disproportionately high court judgments
- Lack of government support for innovation

Likewise, the Transportation Research Board of the National Research Council (1990) pointed out the following six impediments from government agencies in the highway industry.

- Public-sector decision makers who do not reward risk taking or include long term economic analysis.
- Public-sector procurement driven by low-bid process, which discourages contractors with new products or processes.
- Fragmentation within the highway industry spreading out more than 40,000 organizations with an assortment of political, regulatory, and administrative characteristics, as well as differences in size, budget, and staff capabilities.
- No profit motive to stimulate commercial innovation.
- One-time project delivery.
- Limited knowledge of new technologies.

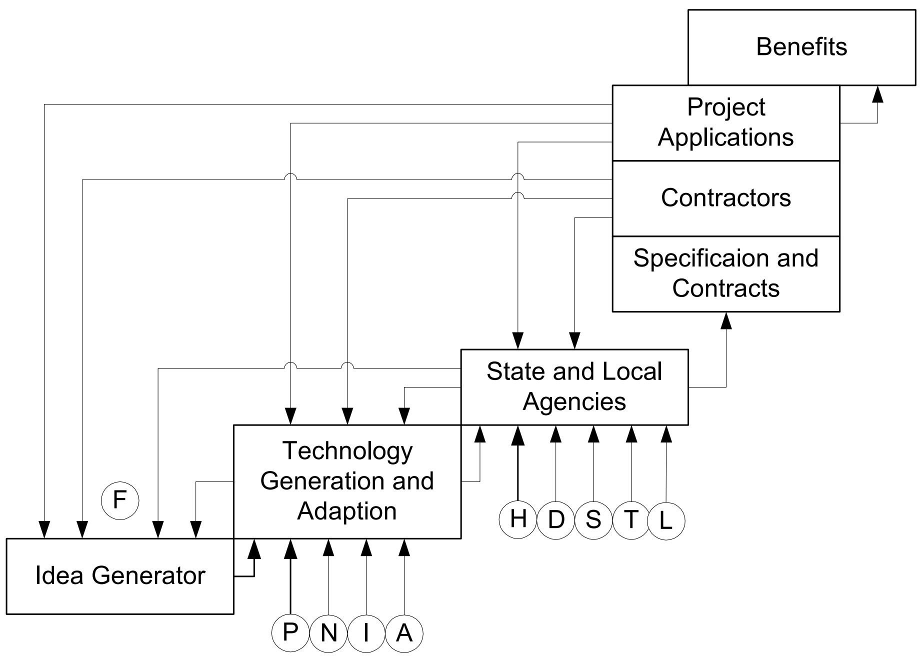
### ***Technology Transfer***

The same report by NRC (1990) proposed a strategy for the Federal Highway Administration (FHWA) to manage technology transfer in the highway industry. Proposed FHWA strategies for technology transfer are as follows:

- Base technology transfer on knowledge about research products and the technology users.
- Set technology transfer priorities.

- Choose appropriate technology transfer methods.
- Measure the effectiveness of technology transfer efforts.

The report also developed a model of the innovation process that incorporates feedback loops and input channels from organizations specifically involved in the highway industry (Figure 2-1).




I : Innovations Deserving Exploratory Analysis
N: National Transportation Product Evaluation Program
H: Highway Innovation Technology Evaluation Center
S: Lead States Program
D: Early Adaptor Support
F: Focus Group (Owner, Highway User Groups, Safety and Environmental Advocates)
L: Local Technology Assistance Program
P: Long-Term Pavement Performance Program
T: National Highway Institute
A: Industry Associations

**Figure 2-1: Technology Innovation Procedures with Input and Feedback by Relevant Participants (NRC 1990)**

Clarifying feedback loops and input channels makes the model efficient, because it can systematically reduce the gap between supply and demand. The following section presents characteristics of the gap between supply and demand in the construction industry.

## 2.5 Gap between Supply and Demand

Technology gaps are found wherever supply does not meet demand. The reasons for such gaps are diverse and often involve the following:

1. *Discontinuity in organizational or individual participation throughout a long timeline starting from research of base technologies to implementation* (Figure 2-2).

Technology supply requires a long period from idea conception to full implementation by end users. Advancing to a subsequent stage with new and diverse participants results in an oversight of crucial components. Such oversights can occur because of the lack of feedback or due to technology limits. Moore (1999) described an adoption process with five stages from the standpoint of end-users attitude toward a new technology, and pointed out the importance of leaping cracks between each stage for the successful life cycle of a new technology.

2. *Industry fragmentation and diverse characteristics* (Figure 2-3).

Fragmentation of the construction industry by diverse project characteristics makes it difficult for suppliers to meet each demand. With limited resources, suppliers naturally focus on the market in high demand.

3. *Lack of or ineffective transfer of information on available technologies between system suppliers and users* (Figure 2-4).

Another gap can be found when failing to acquire information on available technologies or by improperly selecting proper technology. Both come from the ineffective transfer of information on available technologies between suppliers and users. The lack of a comprehensive repository of technology information or systemic evaluation organization can explain this situation.

It is virtually impossible to eliminate the gap due to the complex nature of supply mechanism. Instead, it would be valuable to identify where the largest gaps exist. This information can provide worth while information to suppliers for their future R&D investments, and to users for the adoption of new technology.

| Research ➔ Development ➔ | Demonstration / Verification ➔ | Adoption ➔ | Usage and Training |
|---|---|---|---|
| -Academic organization<br>-Research institute<br>-R&D department<br>-Software vendor<br>-R&D Consortium | -Independent organization<br>-Researcher and developer<br>-Vendor<br>-Government | -Industry entity (Owner, A/E, GC, Subcon.)<br>-Government | -Industry entity and individuals |

Supply aspect — Demand aspect

**Figure 2-2: Gap Generated by a Long Timeline and Diverse Participants**

2.6

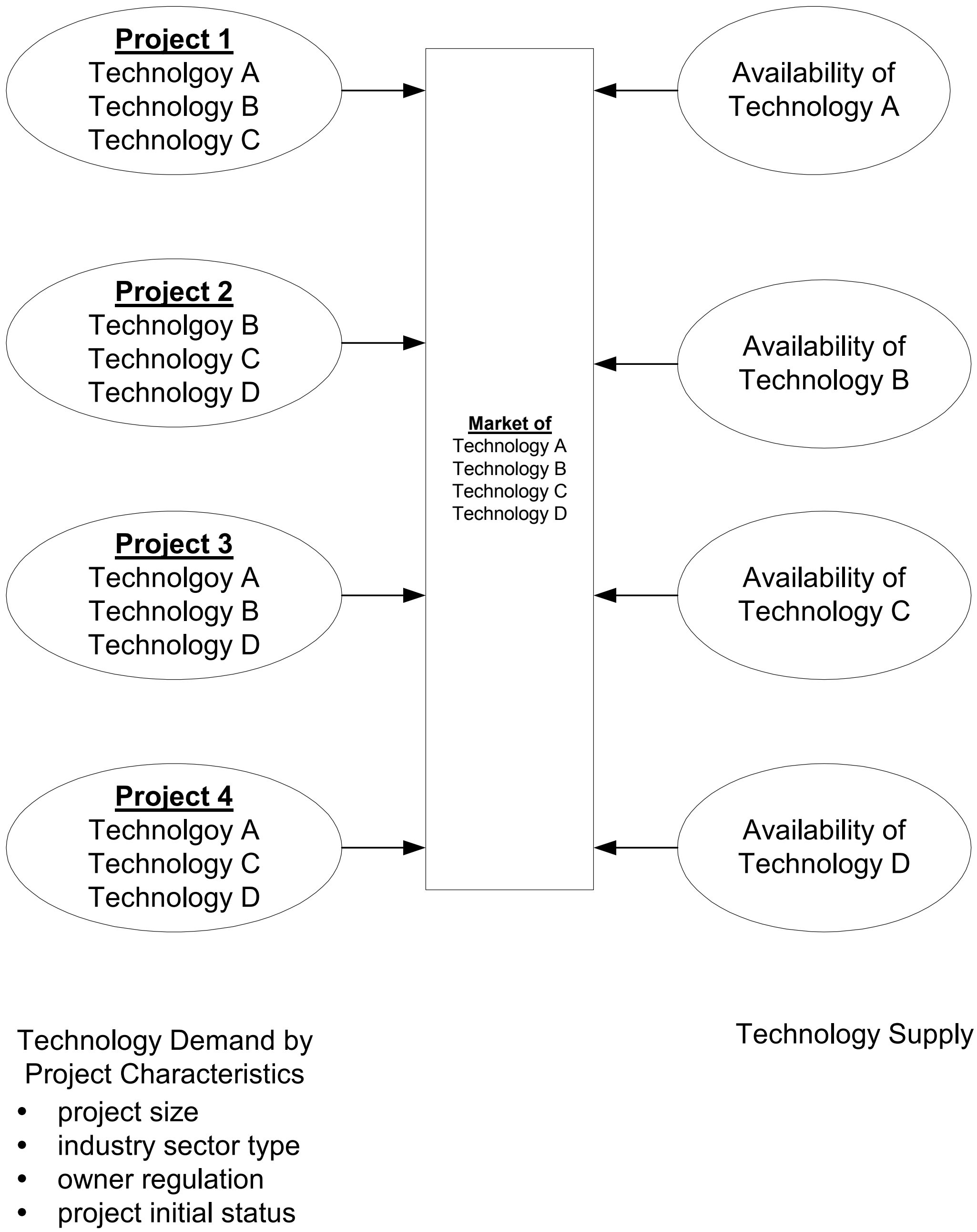



**Figure 2-3: Gap Generated by Industry Fragmentation and Diversity**

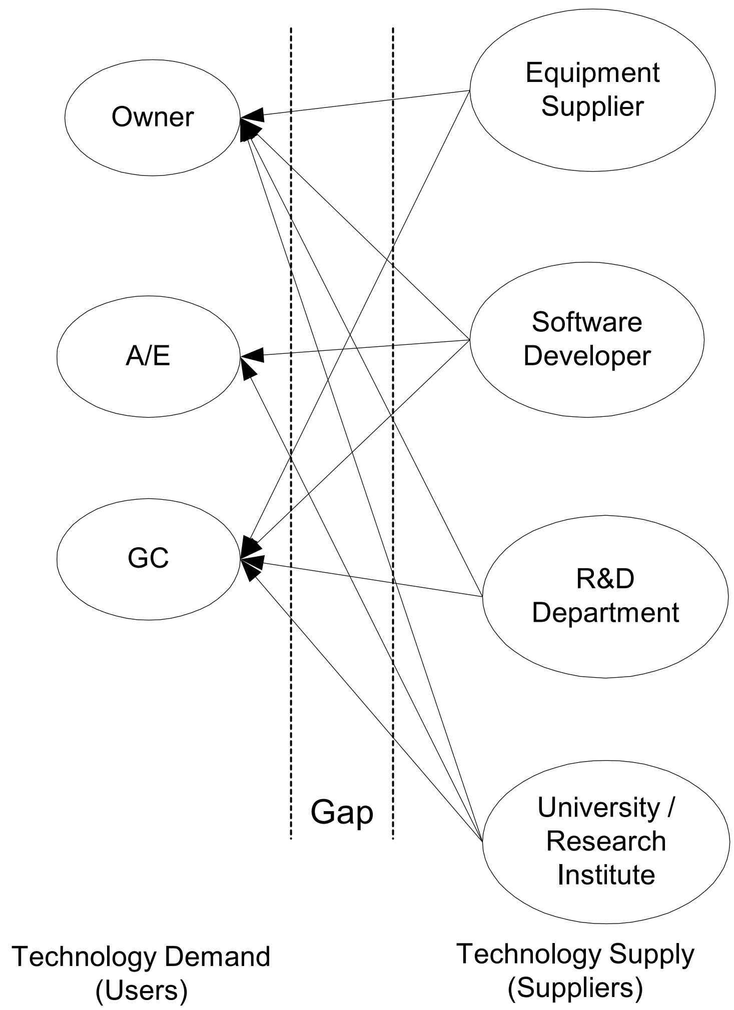



**Figure 2-4: Gap Generated by Lack of or Ineffective Transfer of Information**

## 2.7 Degrees of Current Technology Use in the Construction Industry

### 2.7.1 Technology Usage of Capital Facility Projects in the U.S.

The Center for Construction Industry Studies (CCIS) at the University of Texas at Austin developed industry-wide integration and automation (IA) technology use metrics based upon 68 common project WFs associated with six project phases: Front-End (FE), Design (DS), Procurement (PR), Construction Management (CM), Construction Execution (CE), and Operations & Maintenance (OM). More than 200 capital facility projects distributed across the country were assessed for technology usage between October 1998 and September 1999. Chapter 4 presents a brief introduction to the data collection and data structure, and lists of 68 WFs.

The industry-wide mean value of technology use is 3.85 on a 0 to 10-point scale. This relatively low overall mean value clearly indicates that the construction industry has significant potential for technological advancement.

Several key findings include the following:

- IA technology use differs distinctively by project phase. The highest levels of IA technology use are employed in the Design and Front End Phases, while the lowest ones are associated with the on-site phases of Construction Management and Construction Execution (Figure 2-5).
- Small-size projects show lower levels of technology use than Large- and Medium-size projects.

- Task-to-task integration technologies involve lower levels of use than stand-alone automation technologies.

More detailed statistical analyses of Project and Phase level IA indices calculated by the data class variables are contained in the CCIS Report No.16.

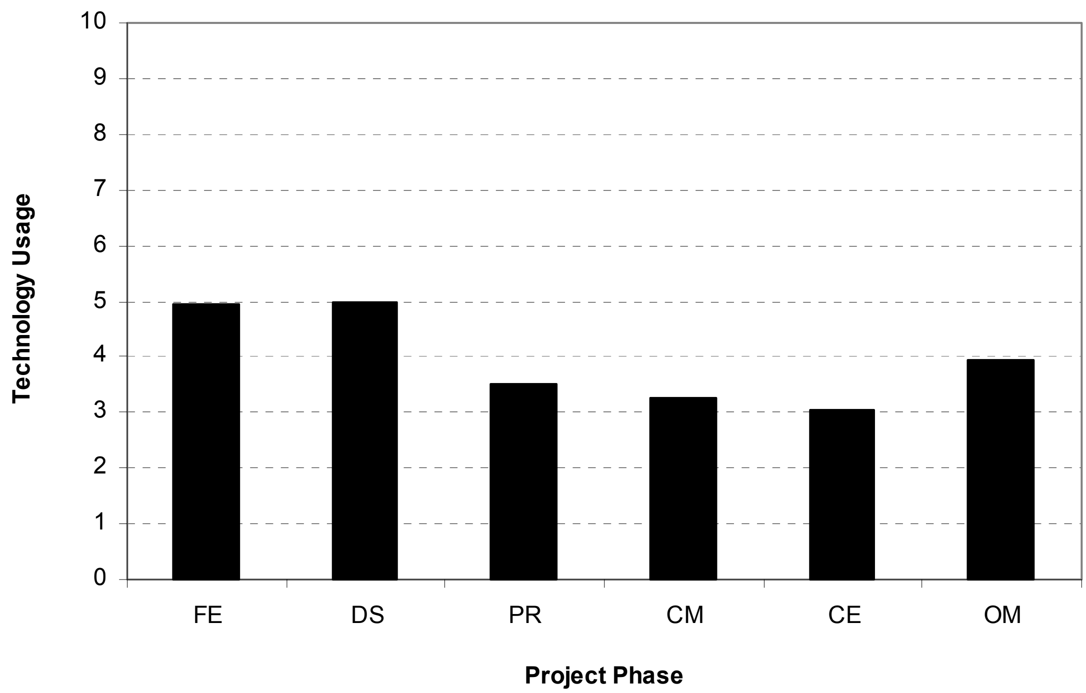



**Figure 2-5: Technology Usage by Project Phase (CCIS Report No.16 2001)**

### 2.7.2 International Competition in Construction Technology

A couple of research studies have compared international competition in construction technology. The CERF report (1994) revealed that the U.S. led other nations in computer-based technologies, while Japan sustained a strong lead in automation and robotics (Table 2-5). An older survey (Halpin 1990) showed similar results, indicating that the U.S. enjoyed higher levels of technology use in data intensive technologies such as CAD, information management systems, and project control. Meanwhile, other European countries or Japan claimed superiority regarding physical-systems technologies mainly applied to the construction execution phase.

**Table 2-5: Leading Countries in Construction Technologies (CERF 1994)**

| | U.S. Leads | Europe Leads | Japan Leads |
|---|---|---|---|
| Technology | - CAD/CAE<br>- GPS/GIS<br>- Integrated database | - Real-time positioning system | - Automated equipment<br>- High-speed pavement assessment<br>- Field computer use<br>- Robotics |
| Facility | - Waste/wastewater treatment<br>- Solid/hazardous waste disposal | - High-speed rail<br>- Tunneling<br>- Marine construction<br>- Energy conservation | - Intelligent building<br>- Building systems |
| Material | - High-performance concrete | - High-performance asphalt | - High-performance steel |

# CHAPTER 3 RESEARCH METHODOLOGY

## 3.1 Research Steps and Main Components

This chapter presents the research methodology in detail. The methodology includes overall research steps, introduction to main components, data analysis methodology, and criteria on further data collection. One of the main challenges is to build a solid theoretical model and methodology that incorporate the previous survey results with further data collections.

Figure 3-1 depicts an overview of the research steps. First, after an understanding of the technology aspects of capital facility projects was developed from the comprehensive literature survey, a list of generalized WFCs for the purpose of assessing technology demand in the capital facility projects was complied. The WFCs should be general and comprehensive enough to apply to common project WFs across the entire range of project phases. Detailed explanations of the process of developing the WFCs list are presented in Chapter 5. Understanding the degrees of technology usage at the WF level is important because the notion of "technology use" is assumed to involve both technology supply and demand. A consistent and reliable data analysis method should be selected. Section 3.2 describes the selected statistical methodology in detail.

With the development of a comprehensive list of WFCs, the study proceeded with two main processes: the Research Proof Model and the Application Model (Figure 3-2).

***Research Proof Model***

The purpose of the Research Proof Model is to prove the value of WFCs as a technology demand driver. There are two key components in the Research Proof Model: the Technology Demand Model and the Technology Supply Model. Two different sets of data collection tools were developed for the Technology Demand Model in order to link between WFCs and technology demand, and characterize WFs. Professionals from the construction industry and academia participated in data collection procedures. The first set of data was aimed at assessing the degree of the technology demand of each generalized WFC. The second set of data was used to characterize a specific WF. Combining these data sets enabled the author to assess each WF's technology demand by means of WFCs.

For the Technology Supply Model, another data collection tool is required for the purpose of characterizing and assessing the supply status of an individual WF. This model should be general and broad enough to assess different types of technologies and tools. Data for the model was collected throughout the literature survey. Sources include magazines, web sites, journals, brochures, and other available materials. A survey of technology end-users could be an alternative; however, the methodology could fail to represent overall status if the amount of data was not large enough. Still, the quality of the supply evaluation depends on how comprehensively the current technology supply in the market and research institutes was surveyed by the author.

For the assessments of both the technology supply and demand, indices for each supply and demand assessment to convert ordinal variables to numeric values were developed. These indices produced a hypothesized technology use from WFCs-based demand, which should be compared with the surveyed technology use. A proper statistical analysis method should be employed to demonstrate how closely the hypothesis can be justified.

***Application Model***

The Application Model was developed for the purpose of prioritizing technology R&D. Combining the proven Technology Demand Model with a knowledge of the surveyed technology use can be a surrogate for technology supply according to Assumption #2. This supply surrogate allows the Application Model to collect data for the demand assessment only, while the Proof Model required data from both the supply and demand model. A demand that is higher than the level of use can indicate higher demand than supply, which suggests a gap between supply and demand. The larger the gap that is found, the higher the priority of technology R&D that can be claimed.  Criteria on data collection and methodology are provided in Section 3.3, and a detailed model development and research results are presented in Chapter 7.

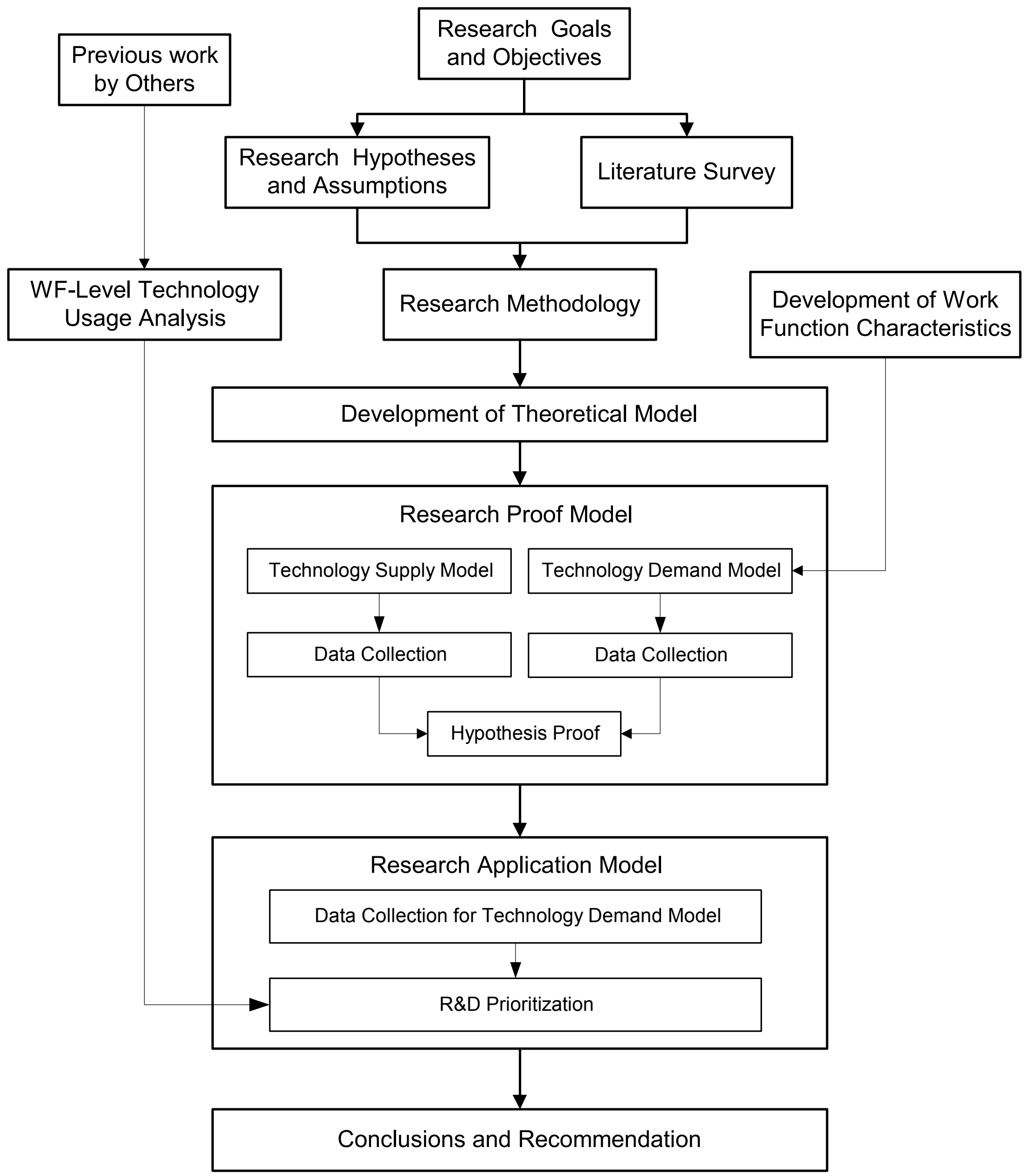



**Figure 3-1: Research Steps**

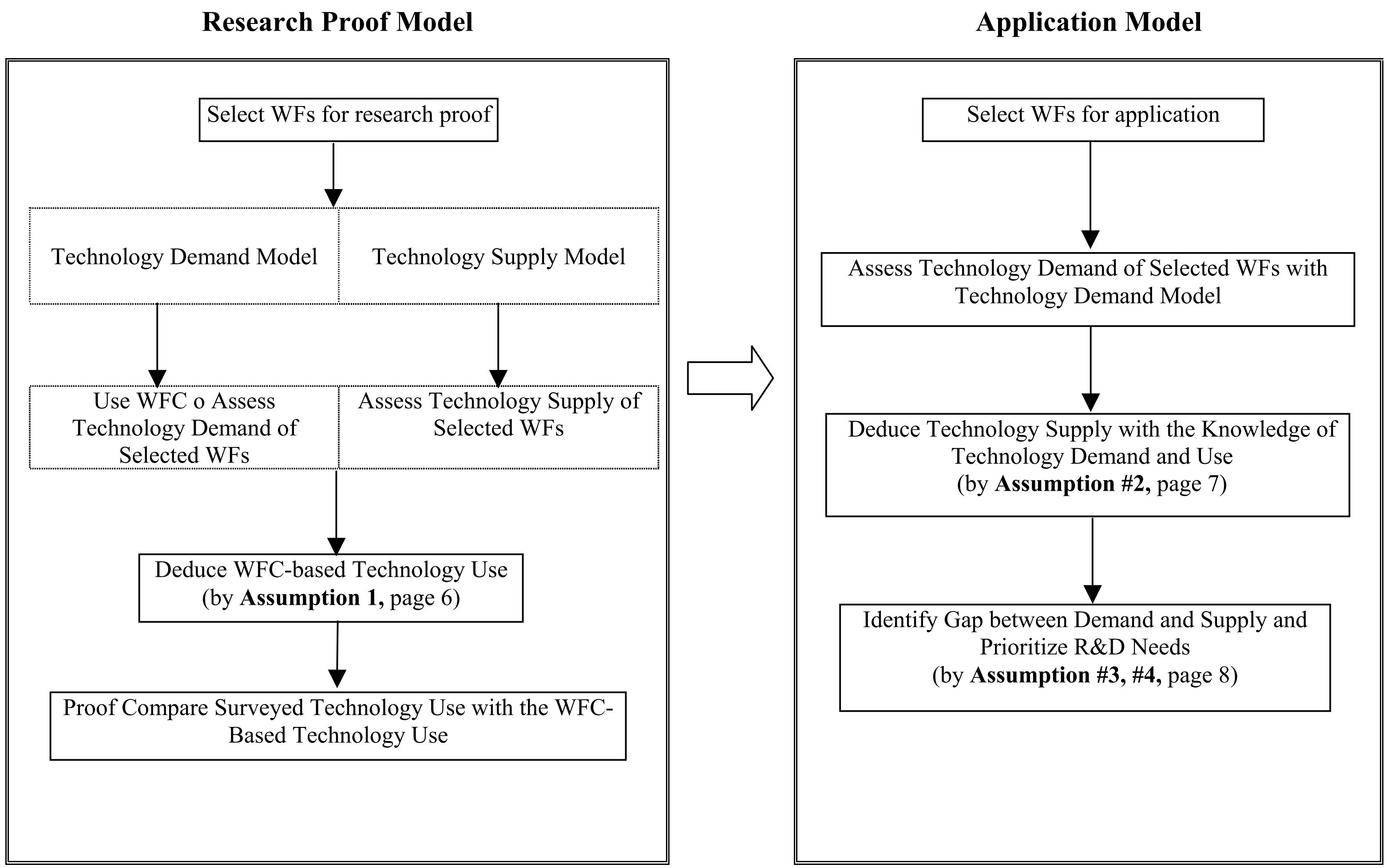



**Figure 3-2: Research Step for the Research Proof Model and Application Model**

## 3.2 Data Collection Methodology

Once the objects of the data collection have been determined, methodology for the data collection should be developed. The Technology Demand Model consisting of an assessment of characteristics of WFs and technology demand necessitates expertise from industry professionals or academia. The data collection tools developed to survey the expertise are presented in Appendix A and Appendix B.

The study relied on literature survey to collect data regarding technology supply. Table 3-1 lists data resources for assessing technology supply. Most resources were created by suppliers rather than users. Emerging base technologies are mostly introduced in papers and journals. The data collections are not necessarily limited to the resources listed below; however, some topic-specific resources were included based on the WFs selected in the Research Proof Model.

**Table 3-1: Data Sources for the Technology Supply Model**

| Source Type | Sources |
|---|---|
| **Tools** | |
| Magazines | ENR, CE News, Constructors, Modern Steel Construction, Concrete Construction, Cost Engineering |
| Information by Suppliers | Brochures, Demo CD-ROMs, Video Tape, Manuals, Supplier's Website |
| Search Engines | yahoo.com, northernlight.com, albert.com, go.com |
| Construction portal websites | construction.com, constructioneducation.com, uscost.com |
| Organization websites | ctsguides.com, gypsum.org |
| **Base Technology** | |
| Journals | ISARC Proceedings, 1993 – 2000<br>Journal of Construction Management and Engineering, 1990-2001<br>Journal of Architectural Engineering, 1990-2001<br>Journal of Aerospace Engineering<br>Journal of Computing in Civil Engineering |
| Organization websites | vtt.fi |
| **Interface Standards** | |
| Journals | Journal of Construction Management and Engineering, 1990-2001<br>Journal of Computing in Civil Engineering |
| Information by Suppliers | Brochures, Demo CD-ROMs, Video Tape, Manuals, Supplier's Website |

## 3.3 Statistical Analysis

### 3.3.1 Mean Comparisons for Technology Use

With regard to IA Metrics, the main consideration at the WF level is where significant differences of technology use exist. In order to test a significant difference between two independent variables the *t*-test can be used, and ANOVA can be applied for a comparison among more than two variables.

The structure of the data sets, which contain 68 mean values at the WF level, requires a large number of tests. The number of tests increases dramatically, if we want to compare sub-grouped means by five data class variables. This data structure inevitably necessitates multiple mean comparisons.

The multiple comparisons need a careful consideration, because they increase "familywise error rate." The familywise error rate is the probability of wrongly rejecting any of a set of true null hypotheses tested in an experiment. When performing k-1 independent tests of significance, the probability that we have committed at least one Type I error ($\alpha_{fw}$) is equal to $1 - (1 - \alpha_{pc})^{k-1}$, where $\alpha_{pc}$ is the level of significance or probability of committing a Type I error per comparison given that the null hypothesis is true. When *k* is large, this can be quite a large probability. For example, when 28 different t-tests between pairs of group means are performed using $\alpha_{pc} = 0.05$, there will be a probability of $1-(.95)^{28}$, or about .76 for at least one Type I error among the multiple comparisons (Hays 1994).

There are a couple of criticisms of the multiple comparison methods. Nelder (1971) and Mead (1988) strongly insisted that multiple comparison methods should be avoided in the interpretation of data sets. When multiple comparisons are made on a *post-hoc* basis, steps should be taken to control for an excessive $\alpha_{fw}$ (Hays 1994).

The structure of the IA Metrics survey, however, makes it impossible to avoid multiple mean comparisons on a *post-hoc* basis. However, several methods exist for handling such *post-hoc* based multiple mean comparisons. Three different options are available: Bonferroni, Scheffé, and Tukey comparisons in the most conservative sequence. In spite of the criticism of being too much conservative, this study adopts Bonferroni comparisons because of an enormous number of comparisons.

The Bonferroni ad-hoc analysis controls overall error rate by setting the error rate for each test to the familywise error rate divided by the total number of tests. Hence, the observed significance level is adjusted for the fact that multiple comparisons are being made (SPSS Manual 2000).

### 3.3.2 Correlation Analysis for Research Proof

The Research Proof Model is designed to prove the hypothesis by observing how closely the WFC-based technology use can explain the actual technology use as reported on the surveys. In order to test whether there is a statistically significant relationship between two variables, the model will employ correlation analysis.

Regression analysis tests the relationship between two variables where clearly one is a dependent variable and the other is an independent variable (Tamhane and

Dunlop 2000). Regression analysis, in general, is applied to build and test a prediction model. Correlation analysis, however, is used to test the strength of the relationship of bivariate data, and this is consistent with the purpose of the Research Proof Model. The correlation analysis is based on the following two assumptions:

- The sample of paired data is a random sample.
- The pairs of data have a normal distribution.

The Proof Model expects a linear relationship, $y = x$, between two variables, because it compares two different data sets of the same variable, technology use, but from independence resources. The correlation coefficient, ***r***, measures the strength of the linear relationship between the paired variables. The following equation was developed by Pearson to compute the correlation coefficient.

$$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{n\sum x^2 - \left(\sum x\right)^2}\sqrt{n\sum y^2 - \left(\sum y\right)^2}}$$

, where $x$ and $y$ are data variables and n is the number of pairs of data.

The value of $r$ always falls between +1 and –1. If $r$ is close to –1 or +1, there is a strong linear correlation between $x$ and $y$. The value of $r$ does not change, if all values of either variable are converted to a different scale (Triola 2001).

Given the number of paired data and $r$, a test statistic with a significance level of $\alpha = .05$ will be performed to determine whether there is a significant linear relationship between the WFC-assessed technology use and the surveyed technology use.

While the value of $r$ represents the strength of direction of linear correlation between two variables, the value of $r^2$ explains to what extent the variation of the independent variable can be explained by the dependent variable. Since this research will compare two like variables, instead of a predicting variable from a given variable, the terminology of “variation of prediction” can be interpreted as “sharing between two variables” (Smith, 2001). Chapter 6 will present the test statistics $r$ and $r^2$ and their interpretation along with surveyed data sets. The WFC-assessed technology use will not necessarily be the exact result of the surveyed technology use, because technology demand is not affected only by the WFCs, but also by other factors such as project characteristics or unique organizational characteristics.

# CHAPTER 4 TECHNOLOGY USAGE BY WORK FUNCTION

## 4.1 Introduction to Previous Research

This chapter starts with a brief introduction to the IA Metrics surveyed by previous graduate students and a summary of the descriptive analysis at the WF level. Survey methodology and data collection results are presented first. Main components of the data collection tool are explained to facilitate understanding of the data analyses. Then, sampling issues for the representativeness of U.S construction industry are presented. Finally, a summary analysis of technology use at the WF level follows.

The IA Metrics project was initiated after researchers acknowledged the lack of industry-wide benchmarking data concerning the levels of technology used across the various phases of capital facility projects. The primary objective of the project was to investigate the extent to which integration/ automation (IA) technologies are being used in executing capital facility projects (O'Connor et al 2001). Welch and Kumashiro, in collaboration with their advisor Dr. James T. O'Connor, have developed a data collection tool and a computation method of IA Metrics, respectively. With the tool, Hadeed, Braden, and Deogaonkar surveyed a total of 209 data sets obtained across the country between fall 1998 and spring 1999. They collected the data sets through personal interviews using the data collection tool.

## 4.2 Data Structure and Summary of Data Collection

The data collection tool consists of three main parts: (1) data class variables and company information, (2) IA technology assessment for 68 WFs, and (3) project performance (Figure 4-1).

The data class variables involve five categories: 1) Owner Regulation, 2) Industry Type, 3) Initial Site, 4) Technology Typicality, and 5) Total Installed Cost. The company information includes company type and size. These variables were used to characterize surveyed projects in analyzing the levels of IA technology use. The technology assessment is divided into six phases: Front End (Phase 1), Design (Phase 2), Procurement (Phase 3), Construction Management (Phase 4), Construction Execution (Phase 5), and Operations/Maintenance (Phase 6). The survey asked participants to assess the degree of technology used in executing each WF for the selected recently completed project. Response options included three levels of technology use: 1, 2, or 3. An example of each level is as follows (Welch 1998):

Level 1 – No electronic tools were used to complete the work function. Information was conveyed verbally or in paper form and transmitted via "snail mail", fax, or courier.

Level 2 – Some electronic tools were used in completing the work function. A machine assisted humans in completing the work function. Information was stored in a stand-alone electronic format and transmitted via isolated electronic media like disks or e-mail.

Level 3 – Fully automated systems were used in completing the work function. A human assisted the machine in doing the work. Information was stored on a fully networked system where all participants can access and share information easily, e.g. network systems.

“Not applicable” and “don’t know” responses were also offered as possible responses.

Four variables are selected to measure project performance: 1) Schedule Performance, 2) Cost Performance, 3) Safety, and 4) Stakeholder Success.

In addition to the data structure listed above, The 68 WFs were classified into two groups, task automation (TA) WFs and integration link (IL) WFs, depending on the boundary applied by technology. For a TA WF, automation technology adds value to a WF by reducing manpower; however, the technology is mostly applied to within the boundary of a specific WF. On the other hand, technology for an IL WF encompasses any or all the types of integration features including intra-organization, inter-discipline, or between phases (Kumashiro 1999). A full list of TA and IL WFs is provided in the CCIS Report No. 16.

Table 4-1 summarizes the frequency of the collected data set by organization type and five data class variables. Percentages of each variable are calculated based on valid responses. Various populations were targeted before data was collected to represent the characteristics of the construction industry as a whole. A number of samples were taken to assess each of the following population variables: Industry Sector, Total Installed Cost, Organization Type and Technical Typicality. A discussion of the sampling method follows in the next section.

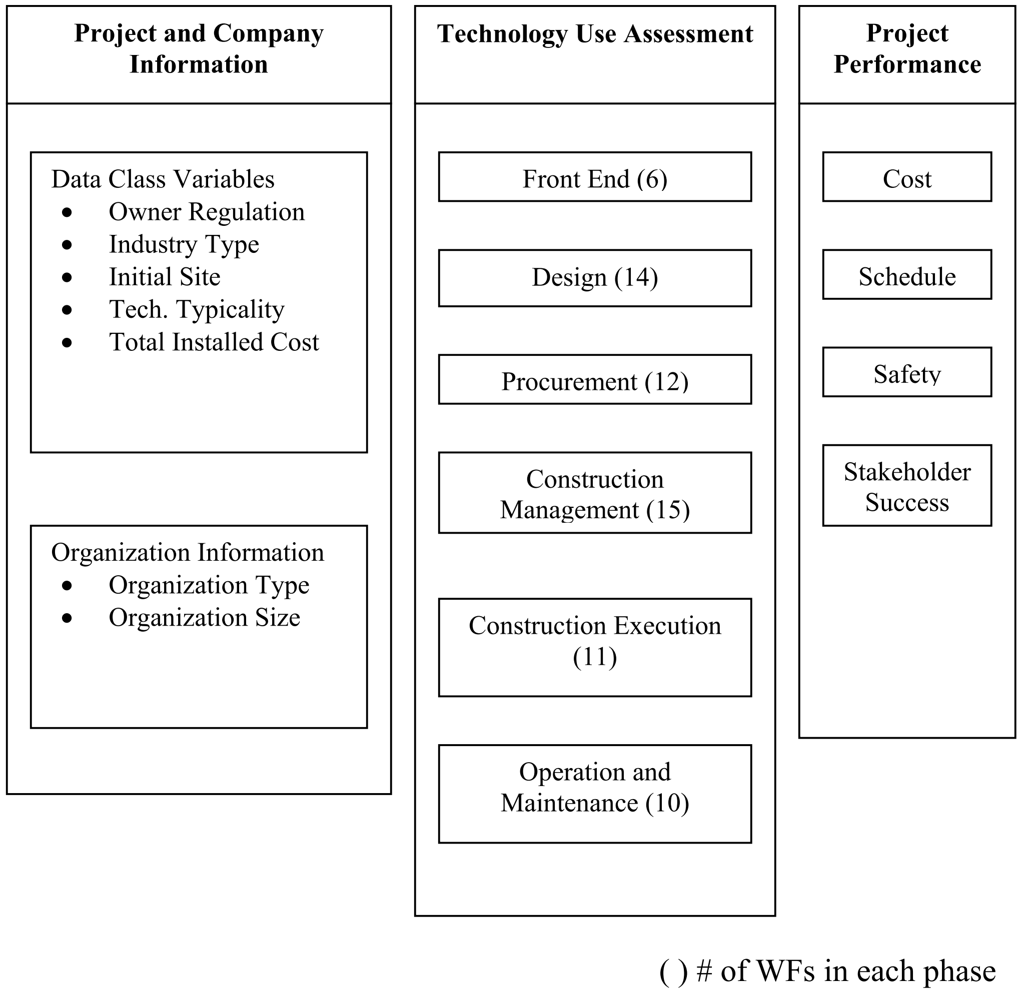



**Figure 4-1: Data Structure of Technology Use Collection Tool**

**Table 4-1: Frequency Table of Data Set by Organization Type and Data Class Variables**

| **Organization Type** | | |
|---|---|---|
| | **N** | **%** |
| Private Owner | 38 | 18.3 |
| Public Owner | 38 | 18.3 |
| Architect / Engineer | 50 | 24.0 |
| General Contactor | 65 | 31.3 |
| EPC | 13 | 6.3 |
| Subcontractor | 4 | 1.9 |
| **Data Class Variables** | | |
| Owner Regulation | | |
| Public | 72 | 34.8 |
| Private | 135 | 65.2 |
| Project Initial Site | | |
| Green Field | 94 | 46.8 |
| Expansion | 61 | 30.3 |
| Renovation | 46 | 22.9 |
| Industry Sector | | |
| Building | 107 | 51.4 |
| Infrastructure | 52 | 25.0 |
| Industrial | 49 | 23.6 |
| Total Installed Cost | | |
| Less than $5 million | 133 | 64.3 |
| $5 million - $50 million | 34 | 16.4 |
| More than $50 million | 40 | 19.3 |
| Technology Typicality | | |
| Advanced | 33 | 16.5 |
| Typical | 167 | 83.5 |

## 4.3 Data Sampling and Representation of Industry

Due to the lack of a complete list of all industry participants as well as the projects they are currently involved in, Kumashiro (1999) suggested a quota sampling method instead of a simple random or cluster sampling method. The quota sampling method is to select separate samples from each of the quota obtained by the classification of the population into subpopulation (Kalton 1983). The sample sizes in the quota are often made proportional to the quota population sizes. To support the quota sampling method, he developed proportional representatives of the four populations in terms of their population characteristics and classes. The targeted and actual mix of surveyed projects is presented in Table 4-2. As shown in Table 4-2, the biggest deviation from the target mix is 8% in Building, and the other variables are equal to or within 5% of the target.

To select participants, the three research assistants referred to various online databases, directories of industry associations, or listings in the phone book. Thirty-two metropolitan areas across the country were surveyed.

**Table 4-2: Summary of Targeted Quota Mix (Hadeed 2000)**

| Population Characteristic | Classes | Targeted Mix (%) | Actual Mix (%) | Deviation (+/-) |
|---|---|---|---|---|
| Industry Sector | Building | 60 | 51.8 | -8 |
| | Industrial | 20 | 23.4 | +3 |
| | Infrastructure | 20 | 24.8 | +5 |
| Total Installed Cost | <$5 Million | 35 | 33.2 | -2 |
| | $5-20 Million | 30 | 29.4 | -1 |
| | $20-50 Million | 15 | 15.9 | +1 |
| | $50-100 Million | 10 | 11.7 | +2 |
| | >$100 Million | 10 | 9.8 | 0 |
| Company Type | Owner | 25-40 | 36.0 | 0 |
| | General Contractors | 25-35 | 40.3 | +5 |
| | A/E Companies | 20-30 | 23.7 | 0 |
| Project Typicality | Typical | 90 | 85.2 | -5 |
| | Advanced | 10 | 14.9 | +5 |

## 4.4 Descriptive Analysis of Technology Usage at the Work Function Level

### 4.4.1 Work Functions with Overall High and Low Technology Use

The mean values of technology use for individual WFs range from 1.43 to 6.70. Thus, technology usage varies significantly by WF. Figure 4-2 (O'Connor and Won 2001) presents a histogram of IA Index means for all 68 WFs. From the mean values, the following list presents ten WFs pertaining to the highest levels of technology usage in descending order.

- WF2.05: Generate facility floor plans
- WF2.08: Design the electrical system and related drawings
- WF2.06: Design the fluid transport system (open channel or pipes) and related drawings

- WF2.07: Design the structural system and related drawings
- WF2.09: Design the HVAC system and prepare related drawings
- WF2.04: Use conceptual design work as a basis for detailed design work (IL)
- WF6.09: Monitor/track/control facility energy usage (IL)
- WF1.05: Develop a milestone schedule from the scope of work
- WF2.12: Prepare project specifications
- WF4.04: Update the current cost forecast

Note that the six highest technology use WFs belong to the Design Phase and are related to CAD technology. This explains the highest level of technology use in the Design Phase shown in Figure 2-5. Not a single WF comes from Phases 3, and 5. Only two out of ten are integration link (IL) WFs, which may indicate that integration technology is far from being top-ranked. On an absolute scale, only one WF could truly be labeled as "high-tech"; "Preparing floor plans," scored a 6.70 on the 10-point scale.

The following 10 WFs, ranging from 1.43 to 2.33 in IA Index value, maintain the lowest levels of technology usage in ascending order:

- WF503: Construct rebar cages
- WF508: Manipulate and hang sheetrock
- WF407: Link field material managers to suppliers (IL)
- WF312: Plan the transportation routes of large items from the fabricator to the job site
- WF411: Communicate design changes to field personnel (IL)
- WF311: Monitor the progress of fabricators (IL)
- WF202: Get input from operators and builders regarding construction methods selection, & construction sequencing (IL)

- WF403: Maintain daily job diary
- WF412: Communicate status of change orders to field (IL)

In contrast to high technology WFs, nine out of ten of the above WFs pertain to Phases 3, 4, and 5. Communication among participants that requires more than simple data transfer belongs to a low level of technology use (WF4.07, WF4.11, WF2.02, and WF4.12). It should be noted that Phase 2, which enjoys the highest level of technology use, suffers from low usage in terms of "constructability."

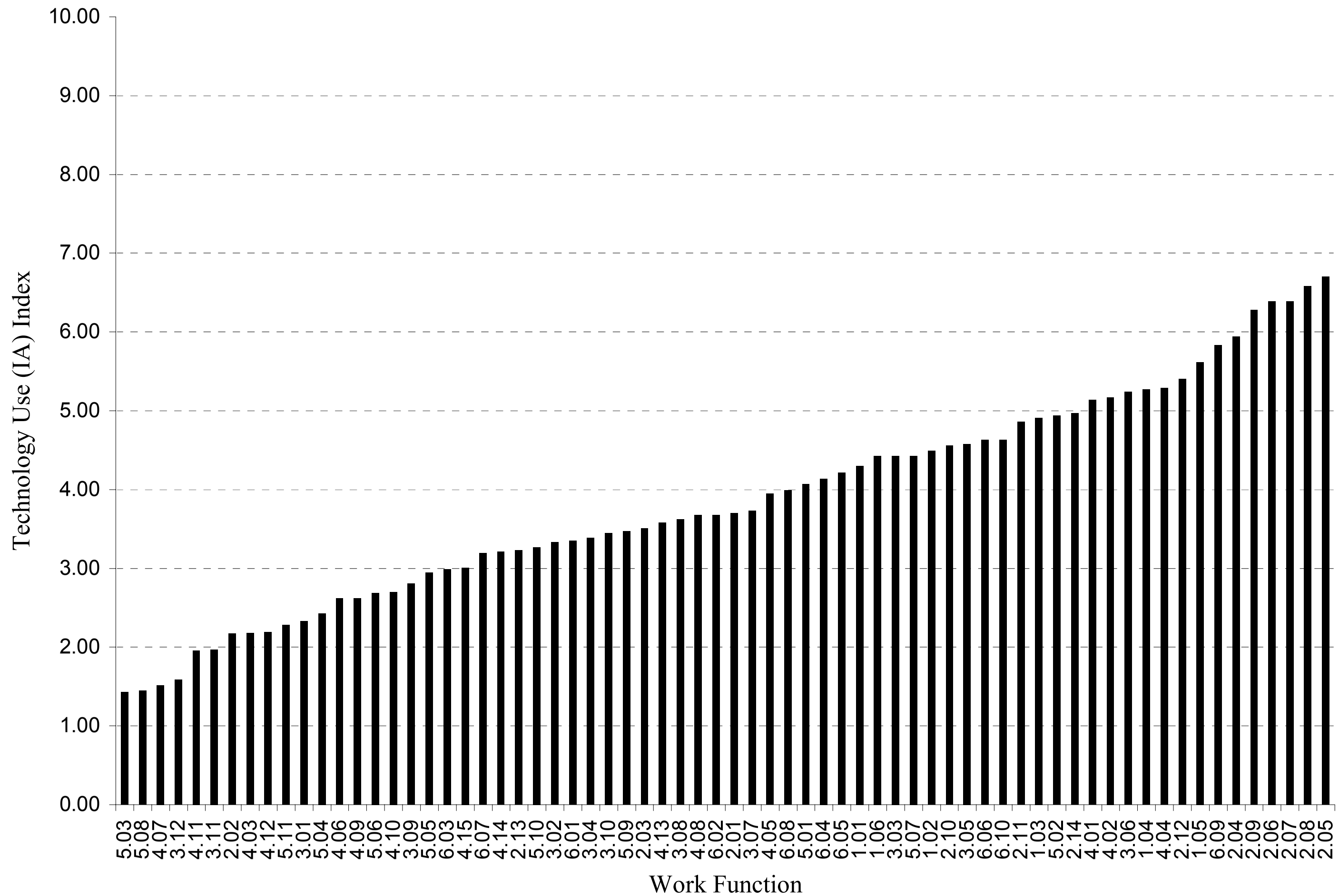



**Figure 4-2: Technology Usage by Work Function (O'Connor and Won 2001)**

### 4.4.2 Descriptive Statistics of Technology Use at the Work Function Level

This section presents a full list of 68 WFs and their descriptive statistics by project phase (Tables 4.3 to 4.8) (O'Connor and Won 2001). Figure 4-3 displays the distribution of technology use by project phase. Phase 2 covers the largest range from 2.17 to 6.67, while Phase 1 contains the smallest range, 4.30 to 5.62. In Phase 4, it is noticeable that three WFs, WF4.01, WF4.02, and WF4.04, which are related to cost or schedule controlling functions, maintain higher levels of technology use than other WFs in Phase 4. Not surprisingly, virtually all of the "high-tech" WFs are data- or information-intensive.

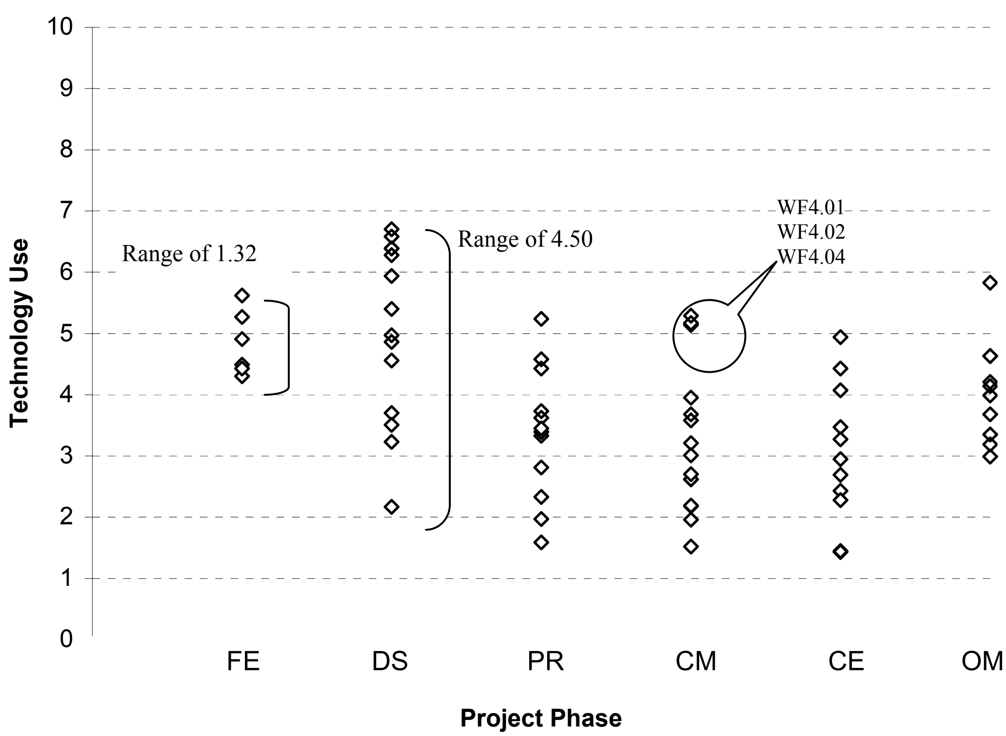



**Figure 4-3: Work Function Technology Use Distribution by Phase**

**Table 4-3: Front-End Work Function Descriptive Statistics (O'Connor and Won 2001)**

| ID | Work Function | N | Mean | Std. Dev. |
|---|---|---|---|---|
| 1.01 | Conduct market analysis or need analysis for a new facility | 86 | 4.30 | 3.36 |
| 1.02 | Develop, evaluate, and refine the project's scope of work | 167 | 4.49 | 3.28 |
| 1.03 | Diagram the manufacturing process -or- the user's processes | 110 | 4.91 | 3.45 |
| 1.04 | Estimate a budget from the scope of work | 182 | 5.27 | 3.14 |
| 1.05 | Develop a milestone schedule from the scope of work | 185 | 5.62 | 2.86 |
| 1.06 | Acquire and store site investigation data for use during design | 149 | 4.43 | 3.56 |

**Table 4-4: Design Work Function Descriptive Statistics (O'Connor and Won 2001)**

| ID | Work Function | N | Mean | Std. Dev. |
|---|---|---|---|---|
| 2.01 | Designers access supplier information in order to select components | 138 | 3.70 | 3.54 |
| 2.02 | Get input from operators and builders regarding construction methods selection, & construction sequencing | 157 | 2.17 | 2.90 |
| 2.03 | Analyze alternative construction methods for effects on cost, schedule, etc. | 161 | 3.51 | 3.57 |
| 2.04 | Use conceptual design work as a basis for detailed design work | 144 | 5.94 | 3.74 |
| 2.05 | Generate facility floor plans | 135 | 6.70 | 3.18 |
| 2.06 | Design the fluid transport system (open channel or pipes) and related drawings | 104 | 6.39 | 3.15 |
| 2.07 | Design the structural system and related drawings | 140 | 6.39 | 3.12 |
| 2.08 | Design the electrical system and related drawings | 133 | 6.58 | 3.10 |
| 2.09 | Design the HVAC system and prepare related drawings | 117 | 6.28 | 3.23 |
| 2.10 | Document the assumptions used in developing the budget, and pass to the next phase | 147 | 4.56 | 3.09 |
| 2.11 | Detect physical interference between systems (i.e. plumbing, electrical, structural, etc.) | 143 | 4.86 | 4.02 |
| 2.12 | Prepare project specifications | 150 | 5.40 | 3.04 |
| 2.13 | Check the design against owner requirements (e.g. design reviews) and code requirements | 147 | 3.23 | 3.87 |
| 2.14 | Track design progress | 150 | 4.97 | 3.50 |

**Table 4-5: Procurement Work Function Descriptive Statistics (O'Connor and Won 2001)**

| ID | Work Function | N | Mean | Std. Dev. |
|---|---|---|---|---|
| 3.01 | Determine the lead time required to order equipment and materials | 165 | 2.33 | 3.10 |
| 3.02 | Conduct a quantity survey of drawings | 159 | 3.33 | 3.31 |
| 3.03 | Link quantity survey data to the cost estimating process | 157 | 4.43 | 3.40 |
| 3.04 | Link supplier cost quotes to the cost estimating process | 165 | 3.39 | 3.45 |
| 3.05 | Refine the preliminary budget estimate | 177 | 4.58 | 3.10 |
| 3.06 | Develop the milestone schedule | 185 | 5.24 | 2.96 |
| 3.07 | Develop and transmit requests for proposal to suppliers and subs | 169 | 3.73 | 3.23 |
| 3.08 | Prepare & submit shop drawings | 156 | 3.62 | 3.19 |
| 3.09 | Acquire & review shop drawings; send response | 180 | 2.81 | 3.35 |
| 3.10 | Compile quotes from suppliers & subs into a bid or proposal package | 165 | 3.45 | 3.20 |
| 3.11 | Monitor the progress of fabricators | 147 | 1.97 | 3.02 |
| 3.12 | Plan the transportation routes of large items from the fabricator to the job site | 104 | 1.59 | 2.89 |

**Table 4-6: Construction Management Work Function Descriptive Statistics (O'Connor and Won 2001)**

| ID | Work Function | N | Mean | Std. Dev. |
|---|---|---|---|---|
| 4.01 | Develop the construction schedule | 182 | 5.14 | 2.90 |
| 4.02 | Track field work progress & labor cost code charges | 173 | 5.17 | 3.18 |
| 4.03 | Maintain a daily job diary | 172 | 2.18 | 3.25 |
| 4.04 | Update the current cost forecast | 173 | 5.29 | 3.13 |
| 4.05 | Keep all project team members up to date on construction progress | 185 | 3.95 | 3.39 |
| 4.06 | Track the inventory of materials on site | 151 | 2.62 | 3.36 |
| 4.07 | Link field material managers to suppliers | 125 | 1.52 | 2.71 |
| 4.08 | Develop short-term work schedules based on labor, equipment, and material availability | 170 | 3.68 | 3.38 |
| 4.09 | Work crews submit and receive answers to Requests for Information | 170 | 2.62 | 3.36 |
| 4.10 | Builders provide feedback about the effects of design changes, made by owner or A/E, on cost and schedule | 174 | 2.70 | 3.25 |
| 4.11 | Communicate design changes to field personnel | 189 | 1.96 | 3.07 |
| 4.12 | Communicate status of change orders to field | 185 | 2.19 | 3.16 |
| 4.13 | Update as-built drawings | 183 | 3.58 | 3.73 |
| 4.14 | Contractors submit requests for payment | 176 | 3.21 | 3.43 |
| 4.15 | Transfer funds from owner's account to contractor | 141 | 3.01 | 3.87 |

**Table 4-7: Construction Execution Work Function Descriptive Statistics (O'Connor and Won 2001)**

| ID | Work Function | N | Mean | Std. Dev. |
|---|---|---|---|---|
| 5.01 | Evaluate subsurface conditions | 140 | 4.07 | 2.79 |
| 5.02 | Carry out earthwork and grading | 161 | 4.94 | 2.30 |
| 5.03 | Construct rebar cages | 143 | 1.43 | 2.42 |
| 5.04 | Weld pipes | 142 | 2.43 | 3.08 |
| 5.05 | Select the appropriate crane for heavy lifts | 139 | 2.95 | 3.12 |
| 5.06 | Provide an elevated work platform | 132 | 2.69 | 2.72 |
| 5.07 | Fabricate roof trusses | 87 | 4.43 | 3.45 |
| 5.08 | Manipulate and hang sheet rock | 114 | 1.45 | 2.46 |
| 5.09 | Acquire & record laboratory test information | 144 | 3.47 | 3.46 |
| 5.10 | Finish concrete surfaces | 150 | 3.27 | 2.84 |
| 5.11 | Apply paint or coatings | 149 | 2.28 | 2.57 |

**Table 4-8: Operation and Maintenance Work Function Descriptive Statistics (O'Connor and Won 2001)**

| ID | Work Function | N | Mean | Std. Dev. |
|---|---|---|---|---|
| 6.01 | Conduct pre-operations testing | 118 | 3.35 | 3.00 |
| 6.02 | Train facility operators (e.g. simulations, software) | 114 | 3.68 | 3.33 |
| 6.03 | Use as-built information in personnel training | 112 | 2.99 | 3.25 |
| 6.04 | Track & analyze the maintenance history of important equipment | 99 | 4.14 | 3.57 |
| 6.05 | Develop maintenance plans from maintenance history data | 95 | 4.21 | 3.37 |
| 6.06 | Monitor & assess equipment operations | 107 | 4.63 | 3.61 |
| 6.07 | Facility operators request maintenance or modifications | 102 | 3.19 | 3.43 |
| 6.08 | Update as-built drawings in response to facility modifications | 119 | 3.99 | 3.29 |
| 6.09 | Monitor/track/control facility energy usage | 84 | 5.83 | 3.94 |
| 6.10 | Monitor environmental impact of facility operations (e.g. air / water quality) | 80 | 4.63 | 3.71 |

### 4.4.3 Summary of Technology Use by Data Class Variables

The previous section provides descriptive statistics of individual WFs' technology use without considering project characteristics that correspond to data class variables in the survey. However, technology use of a single WF can be significantly different depending on project characteristics. For example, because of the massive quantity and broad area to be covered, earthwork in an infrastructure project may employ more advanced technology tools than in a building project. Another group of significant differences of technology use can be expected between large-size and small-size projects.

This section presents multiple mean comparisons of 68 WFs' technology use in combination with five data class variables; 1) Owner Regulation, 2) Industry Type, 3) Initial Site, 4) Technology Typicality, and 5) Total Installed Cost.

Although this study does not intend to statistically prove any significant differences because of possible multiple comparison errors, consistent and conservative ad-hoc analyses can provide plausible insights into the levels of technology use. Tables 4-9 to 4-14 summarize the results of the multiple mean comparison carried out by a Bon-Ferroni test. A total of 34 significant differences are found associated with 21 WFs. The Construction Management Phase generates the greatest number of significant differences among its nine WFs. This result can explain that the levels of technology use during the Construction Management Phase have wider variances than other phases. By combining with data class variables, it can be interpreted that many attempts to adopt new technologies are undertaken particularly in advanced or large-scale projects.

Among 34 significant differences, 19 are relevant to project size. Project size appears to be a factor in the levels of technology use. Twelve out of the 19 significant differences indicate that Medium size projects, $5 million and $50 million of Total Installed Cost, report higher levels of use than the other sizes. This analysis result seems to contradict the assumption commonly accepted by industry professionals: the larger the project size, the higher the level of technology use. Indeed, high quantity of work and long project periods can provide an opportunity for high return of investment from new technology adoption.

One possible explanation for this result is that the distance from the current level of integration and automation to a fully integrated and automated project processes in Large size projects may be longer than that in Medium size projects, even though Large size projects involve more technology uses than other size projects. This notion could lead the respondents from Large size projects to assess technology usage relatively low.

The second major factor that differentiates usage levels is technology typicality. This is not surprising at all because advanced technology involved projects naturally adopt high level technologies more than typical projects.

It is also reasonable that WF3.03, which is critical procurement activity in public sector projects, shows a significantly higher use in Public projects than in Private projects. A similar interpretation can be applied to WF2.12 by recognizing that Infrastructure projects are mostly Public projects. Preparation of contract documents such as specification is emphasized more strongly in the Public sector than in the Private sector.

**Table 4-9: Significant Difference by Class Variables in Phase 1**

| ID | Work Function | High use | Low use |
|---|---|---|---|
| 1.03 | Diagram the manufacturing process | Infrastructure | Building |

Ad-hoc analysis by Bonferroni option, $\alpha$<.05

**Table 4-10: Significant Differences by Class Variables in Phase 2**

| ID | Work Function | High use | Low use |
|---|---|---|---|
| 2.01 | Designers access supplier information in order to select components | Medium | Small |
| 2.04 | Use conceptual design work as a basis for detailed design work | Large | Small |
| 2.07 | Design the structural system and related drawings | Green field | Renovation |
| | | Medium | Small |
| | | Large | Small |
| 2.09 | Design the HVAC system | Medium | Small |
| 2.12 | Prepare project specification | Infrastructure | Industry |
| | | Medium | Small |

Ad-hoc analysis by Bonferroni option, $\alpha$<.05

**Table 4-11: Significant Differences by Class Variables in Phase 3**

| ID | Work Function | High use | Low use |
|---|---|---|---|
| 3.03 | Link quantity survey data to the cost estimating process | Pubic | Private |
| | | Medium | Small |
| 3.12 | Plan the transportation routes of large items from the fabricator to the job site | Medium | Large |

Ad-hoc analysis by Bonferroni option, $\alpha$<.05

**Table 4-12: Significant Differences by Class Variables in Phase 4**

| ID | Work Function | High use | Low use |
|---|---|---|---|
| 4.01 | Develop the construction schedule | Large | Small |
| | | Medium | Small |
| | | Advanced | Typical |
| 4.02 | Track field work progress & labor cost code charges | Medium | Small |
| 4.03 | Maintain a daily job diary | Advanced | Typical |
| 4.04 | Update the current cost forecast | Large | Small |
| | | Medium | Small |
| | | Advanced | Typical |
| 4.05 | Keep all project team members up to date on construction progress | Advanced | Typical |
| 4.06 | Track the inventory of materials on site | Large | Small |
| | | Medium | Small |
| 4.08 | Develop short-term work schedules based on labor, equipment, and material availability | Medium | Small |
| 4.13 | Update as-built drawings | Large | Small |
| | | Medium | Small |
| 4.15 | Transfer funds from owner's account to contractor | Industry | Building |
| | | Advanced | Typical |

Ad-hoc analysis by Bonferroni option, $\alpha<.05$

**Table 4-13: Significant Differences by Class Variables in Phase 5**

| ID | Work Function | High use | Low use |
|---|---|---|---|
| 5.03 | Construction rebar cage | Industry | Building |
| | | Advanced | Typical |
| 5.06 | Provide an elevated work platform | Large | Medium |
| | | Advanced | Typical |

Ad-hoc analysis by Bonferroni option, $\alpha<.05$

**Table 4-14: Significant Differences by Class Variables in Phase 6**

| ID | Work Function | High use | Low use |
|---|---|---|---|
| 6.03 | Use as-built information in personnel training | Advanced | Typical |
| 6.04 | Track & analyze the maintenance history of important equipment | Expansion | Green field |

Ad-hoc analysis by Bonferroni option, $\alpha<.05$

## 4.5 Work Functions Linked to Project Performance

Another possible analysis at the WF level is to identify WFs linked to project performances. Of the four project performance variables presented in the survey, this study focuses on two: cost performance and schedule performance.

Procedures to identify the WFs associated with project performance are straightforward. With two separate data sets reporting significantly high and low performance respectively, the 10 high-technology-use WFs are selected from both sets. In Table 4-15 and Table 4-16, WFs appearing in both performances are strikethrough. The next step is simply to identify WFs that appear only in the high performance data set. These relatively high-technology-use WFs can be linked to a positive project performance. Likewise, with the same data sets, the 10 low-technology-use WFs are selected from both sets and then WFs that appear only in the low performance data set are selected. These relatively low-technology-use WFs are assumed to negatively affect project performance because of their low levels of technology use.

Table 4-15 presents the WFs in bold letters assumed to be linked to the cost performance. The beneficial WFs are as followings;

- WF1.01: Conduct market analysis or need analysis for a new facility
- WF1.03: Diagram the manufacturing process -or- the user's processes
- WF2.04: Use conceptual design work as a basis for detailed design work
- WF4.02: Track field work progress & labor cost code charges
- WF5.02: Carry out earthwork and grading

Two WFs are identified as WFs detrimental to the cost performance:

- WF4.09: Work crews submit and receive answers to Requests for Information
- WF4.10: Builders provide feedback about the effects of design changes, made by owner or A/E, on cost and schedule

**Table 4-15: Work Functions Associated with Cost Performance**

| Cost Performance | Significantly Over Performance | Significantly Under Performance |
|---|---|---|
| 10 Highest Technology-Use WFs | ~~WF2.08~~ | WF1.04 |
| | ~~WF2.09~~ | WF4.01 |
| | ~~WF2.05~~ | WF1.05 |
| | ~~WF2.06~~ | ~~WF2.08~~ |
| | **WF2.04** | ~~WF2.09~~ |
| | **WF4.02** | WF2.12 |
| | ~~WF2.07~~ | WF5.07 |
| | **WF5.02** | ~~WF2.05~~ |
| | **WF1.01** | ~~WF2.06~~ |
| | **WF1.03** | ~~WF2.07~~ |
| 10 Lowest Technology-Use WFs | WF2.13 | ~~WF5.08~~ |
| | ~~WF4.03~~ | ~~WF3.12~~ |
| | WF5.08 | ~~WF2.02~~ |
| | ~~WF4.12~~ | ~~WF5.03~~ |
| | WF3.11 | ~~WF4.12~~ |
| | ~~WF4.11~~ | ~~WF4.07~~ |
| | ~~WF2.02~~ | **WF4.09** |
| | ~~WF5.03~~ | ~~WF4.03~~ |
| | ~~WF3.12~~ | ~~WF4.11~~ |
| | ~~WF4.07~~ | **WF4.10** |

The beneficial and detrimental WFs associated with the schedule performance are shown in bold letters in Table 4-16. Beneficial WFs to schedule performance are the following.

- WF1.02: Develop, evaluate, and refine the project's scope of work
- WF1.03: Diagram the manufacturing process -or- the user's processes

- WF2.11: Detect physical interference between systems
- WF3.06: Develop the milestone schedule
- WF5.02: Carry out earthwork and grading

Another five WFs are assumed as detrimental WFs in schedule performance.

- WF3.01: Determine the lead time required to order equipment and materials
- WF3.02: Conduct a quantity survey of drawings
- WF3.09: Acquire & review shop drawings; send response
- WF4.09: Work crews submit and receive answers to Requests for Information
- WF4.10: Builders provide feedback about the effects of design changes, made by owner or A/E, on cost and schedule

**Table 4-16: Work Functions Associated with Schedule Performance**

| Schedule Performance | Significantly Over Performance | Significantly Under Performance |
|---|---|---|
| 10 Highest Technology Use WFs | ~~WF2.05~~ | WF4.02 |
| | **WF1.03** | ~~WF1.05~~ |
| | **WF2.11** | WF4.04 |
| | ~~WF1.05~~ | ~~WF2.12~~ |
| | **WF1.02** | ~~WF2.04~~ |
| | **WF5.02** | ~~WF2.05~~ |
| | ~~WF4.02~~ | WF2.08 |
| | ~~WF2.04~~ | WF2.09 |
| | ~~WF2.12~~ | WF2.07 |
| | **WF3.06** | WF2.06 |
| 10 Lowest Technology Use WFs | WF2.13 | ~~WF5.03~~ |
| | ~~WF2.02~~ | ~~WF4.07~~ |
| | WF3.12 | **WF4.10** |
| | ~~WF4.11~~ | ~~WF2.02~~ |
| | WF4.06 | ~~WF4.11~~ |
| | WF4.03 | ~~WF3.11~~ |
| | WF5.08 | **WF3.02** |
| | ~~WF3.11~~ | **WF3.01** |
| | ~~WF5.03~~ | **WF3.09** |
| | ~~WF4.07~~ | **WF4.09** |

WF 1.03 and WF 5.02 are assumed as beneficial WFs in both performances. It should be noted that the detrimental WFs are found only in the Procurement and Construction Management Phases, and these WFs involve communication activity with other parties: WF 3.01, WF3.09, WF4.09, and WF4.10.

# CHAPTER 5 WORK FUNCTION CHARACTERISTICS

## 5.1 Introduction

Work function characteristics (WFCs) are descriptive features that characterize and differentiate one work function from another. The main purpose of WFCs is to explain certain aspects related to a WF. No WF can be described by one characteristic. Instead, each WF is weighted by a list of WFCs.

Although the concept of WFCs is not new at all, no research has been conducted to value them as technology demand drivers. O'Connor (1983) in his dissertation research was the first to develop a comprehensive list of work characteristics. He identified 52 work characteristics and applied them as constructability differentiae in four different work categories. Because his research specifically focused on constructability, the characteristics were mostly limited to those in the construction phase. Because this study deals with WFs across the entire project phases, more inclusive WFCs should be developed.

## 5.2 Framework for Work Function Characteristics Development

Figure 5.1 depicts a framework for an inclusive WFCs development. The framework starts with an investigation of the characteristics and factors affecting technology usage in capital facility projects. Three different levels, organization, project, and project phase, are identified to classify the investigated characteristics and factors.

Independently, commonly recognized main attributes of WFs followed by categories of WFCs provide clues for identifying WFCs. A comprehensive list of WFCs is developed under the WFC categories.

Linking project phase characteristics and WFCs finalizes the framework.

Detailed explanations of development processes are presented in the following sections as indicated in Figure 5.1.

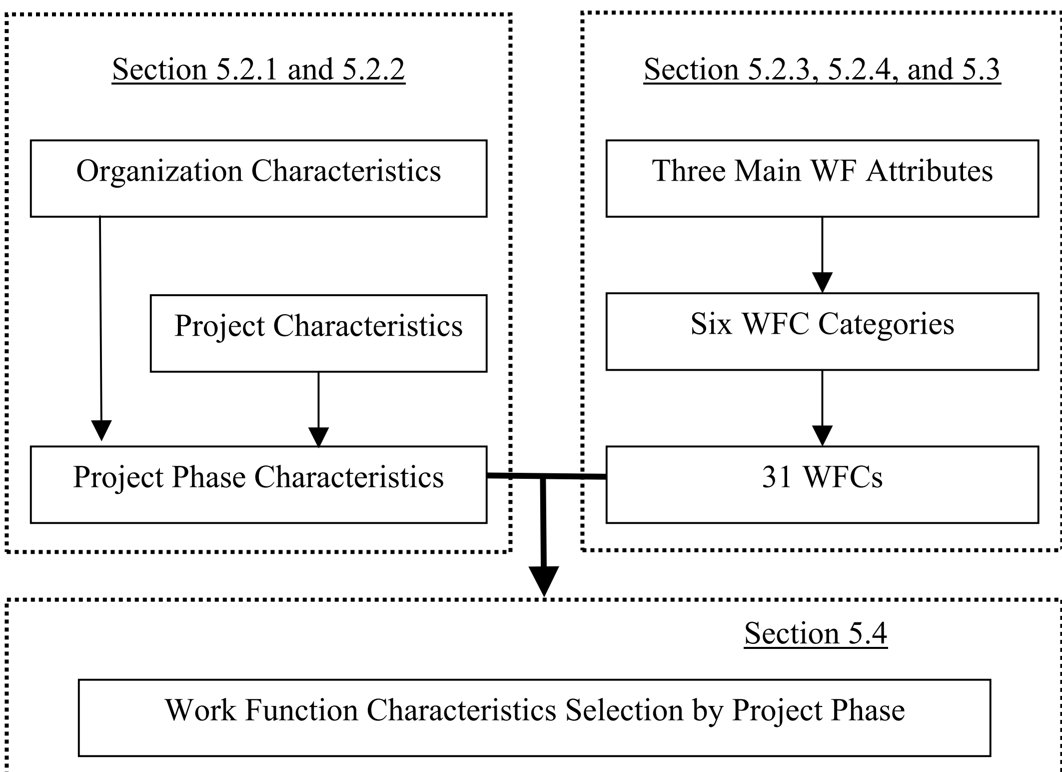



**Figure 5-1: Framework of Work Function Characteristics Development**

### 5.2.1 Characteristics of Capital Facility Projects Affecting Technology Usage and Demand

In Chapter 2, a comprehensive literature survey on the technology aspects of capital facility projects is presented. The literature survey shows that technology usage and opportunities vary by diverse characteristics and factors in different levels. These levels include organization type, project characteristics, project phase, and work function. Four different hierarchical levels are found, where work function is located at the lowest level (Figure 5-1).

Note that the level above work function is project phase. This implies that individual WFs in the same phase may share their characteristics in common the most. Therefore, understanding project phase characteristics can help to identify the characteristics applicable to various WFs in the same phase.

Tables 5-1 to 5-3 list the characteristics and factors affecting technology use by each level.

**Table 5-1: Organization Characteristics Affecting Technology Usage and Demand**

| Category | Characteristics Associated with Technology Usage |
|---|---|
| **Organization** | |
| Public Owner | • Driven by regulatory procedures<br>• Repetitive facility type<br>• Can provide industry with incentive for higher level of technology use<br>*Other Factors*<br>o New regulations |
| Private Owner | • Can provide GC with incentive for higher level of technology use<br>• Flexible project delivery<br>*Other Factors*<br>o Frequency of Capital Facility Project<br>o Diversity of Facility Type<br>o Attitude toward new technology |
| A/E | • Less physical activities, more data-driven activities<br>*Other Factors*<br>o Company size (Annual Revenue Size) |
| EPC | • Better chance of higher level of integration |
| General Contractor | • Major technology implementer and user<br>• Can lead subcontractors to higher level of technology use<br>*Other Factors*<br>o Company size (Annual Revenue Size) |
| Subcontractor | • Less ability to in-house R&D than large GC<br>• Specialized domain in implementing technology |
| Supplier /vendor | • Major suppliers of new technology<br>*Other Factors*<br>o Company size (Annual Revenue Size) |
| Research Institute / University | • Major supplier of base technology<br>• Major developer of advanced technology |

**Table 5-2: Project Characteristics Affecting Technology Usage and Demand**

| Category | Characteristics Associated with Technology Usage |
|---|---|
| **Owner Regulation** | |
| Public | • More regulatory procedures |
| Private | • Flexible project delivery |
| **Project Delivery** | |
| Design-Bid-Build | • Highly fragmentation |
| Design-Build | • Greater chance of higher level of integration<br>• Greater chance of constructability reflection |
| Build-Operation-Transfer | • Greater chance of higher level of integration |
| **Project Size** | |
| Large size | • Greater chances to adopt and customize advanced technology from high ROI<br>• More complex<br>• Less frequency than small size projects |
| Medium size | • Higher level of integration and automation |
| Small size | • Less attention by technology providers<br>• Dominating in number of projects<br>• Fewer team talents |
| **Initial Status** | |
| Green Field | • Relatively fewer restrictions than other Initial Status projects |
| Expansion | • Similar characteristics to Green Field with more spatial restrictions |
| Renovation | • More spatial restrictions<br>• Safety concerns<br>• Impact on operation |
| **Industry Sector** | |
| Building | • Diverse materials handling<br>• Repetitive activities-vertically<br>• Aesthetics issues |
| Infrastructure | • Mostly public sector<br>• Repetitive activities-horizontally<br>• Highly dependent on heavy equipment |
| Industrial | • Higher level of module system<br>• Emphasis on O&M<br>• Complex O&M |

**Table 5-3: Characteristics Affecting Technology Usage and Demand by Project Phase and Work Function**

| Category | Characteristics Associated with Technology Usage |
|---|---|
| **Project Phase** | |
| Front End | • Uncertain and probabilistic data<br>• Less organization involvement<br>• High impact on following phases |
| Design | • Data-driven WFs<br>• Production of massive project information and data<br>• Industry codes and standards |
| Procurement | • Multiple organizations involvement<br>• Organizations dispersed geographically<br>• Security for fair competition particularly in public projects<br>• Heavy data transfer among intra-organizations |
| Construction Management | • Communication-intensive<br>• Dynamic project control<br>• Management as driver |
| Construction Execution | • Physical related WFs<br>• Safety and environment concerns<br>• Spatial coordination of workers, equipments, and materials<br>• Physical resources required to change or fix errors<br>• Logistics<br>• Affected by weather |
| Operation & Maintenance | • Long-term and repetitive activities<br>• Personnel training<br>• Safety concerns |
| **Work Function** | |
| 68 Work Functions in this study | • Human resources aspects<br>• Nature of work function products<br>• Time/Space/Cost factors<br>• Information and data factors<br>• Management factors<br>• Nature of work function procedures |

### 5.2.2 Characteristics of Project Phases

Classification of project phases is based on the structure of the IA Metrics survey. Common characteristics of each project phase found in a typical design-bid-build delivery are explained below.

The Front-End Phase, or project planning phase, is recognized as the most influential phase over the entire project life. However, project stakeholders face a lack of detailed information and must deal with a high degree of uncertainty. Historical data from previous projects is frequently referred to during project planning. Fewer organizations are involved compared with the following phases.

WFs in the Design Phase relate to project contract documents, drawings and specifications. A/E or design companies utilize software tools for engineering analysis and CAD systems for generating plans. Most WFs in this phase are data intensive, while some emphasize communication with the owner or general contractor.

The Procurement Phase generates a sharp increase of project participants. The general contractor, sub contractors, suppliers and vendors are involved according to the contract documents generated in the Design Phase. A tremendous amount of data transfer and communication among relevant organizations occurs. In public sector projects, security and regulatory procedures are emphasized.

WFs in the Construction Management Phase include both data intensive features and frequent interactions among project participants. Additionally, tools and technologies should cope with dynamic situations.

The Construction Execution Phase involves physical resources related WFs. WFs involve materials, workers, and equipment and produce physical products. Spatial coordination or logistics by management can affect physical resource performance to a considerable degree. Safety concerns regarding workers and environmental contamination must be considered. Tools and machines must accommodate external factors on a job site such as temperature, humidity, precipitation, and wind.

In general, the owner gains a full responsibility for the WFs in the Operation and Maintenance Phase. Data from previous phases, i.e., as-built drawings and facility specifications, play a critical role in efficient operations. WFs mostly engage long-term and repetitive activities.

Although the study assumes that all the WFs in a particular phase inherit similar characteristics from that phase, not every WF can be explained by phase characteristics. Furthermore, when considering the same WF in different types of projects, it is important to note that a combination of project characteristics can change the WF's characteristics dramatically. For example, when executing external walls of a high-rise building, the WF5.11 (Apply paint or coating) involves a high level of worker's safety concern, while painting marks and signs in a new highway project does not.

### 5.2.3 Main Attributes of Work Function Characteristics

In addition to hierarchical characteristics explained in the previous two sections, some distinctive work function characteristics affecting technology usage can be grouped by defining three overall attributes as follows:

- Data-intensive WFs
- Physical resource-related WFs
- Communication-oriented WFs

Data-intensive WFs exist throughout the entire project life, although the amount and usage of data varies by project phase. All the activities related to data or document production and project analysis or decision making fall into this category.

Physical resource-related WFs deal with physical objects such as labor, equipment, and materials utilized during the Construction Execution and Operation and Maintenance Phases.

Communication-oriented WFs involve activities such as information inquiry, data submission, meetings, work order delivery, and any transactions between individuals or organizations. Although in recent years more emphasis has been placed on these types of WFs in Front-End Phase, a sharp increase occurs in the Procurement Phase, as contractors and suppliers are chosen.

### 5.2.4 Category of Work Function Characteristics

After identifying three main attributes of WFs and project phase characteristics, six different categories of WFCs are identified; (1) Nature of Human

Resource, (2) Nature of WF Product, (3) Time/Space/Cost factors, (4) Information and Data aspect, (5) WF Management, and (6) Nature of WF Procedure. Table 5-4 relates these six WFCs categories to project phases, divided into groups according to the three different WF attributes. For example, four WFC categories, Information and Data, Work Procedure, Human Resource, and Management, are mainly involved in characterizing data intensive WFs. These data intensive WFs are primarily related to the Front End, Design, Procurement, and Construction Management Phases. The relationships among the WFC category, project phase, and attribute play a basis role in developing a comprehensive list of WFCs and grouping them by project phase.

**Table 5-4: Attributes, Categories, and Relevant Phases for Work Function Characteristics**

| Attribute | WFC Category Most Relevant | Project Phase | |
|---|---|---|---|
| | | Major | Minor |
| Data intensive | Information and Data<br>Work Procedure<br>Human Resource<br>Management | FE<br>DS<br>PR<br>CM | CO<br>OM |
| Physical resource related | Human Resource<br>Work Product<br>Work Procedure<br>Cost/Time/Space<br>Management | CO<br>OM | DS<br>PR<br>CM |
| Communication oriented | Management<br>Work Procedure<br>Human Resource | DS<br>PR<br>CM | FE<br>CO<br>OM |

## 5.3 Work Function Characteristics Development

In order to identify WFCs in each of the six categories, several criteria are established.

- The WFC should be general and comprehensive enough to apply several WFs.
- At the same time, the WFC should play a role as differentiae of WFs.
- The WFC should be related to the anticipated benefits from technology advancement.

Keeping in mind these criteria, the author identified 31 WFCs affecting technology demand (Table 5-5). Some rational behind the selected WFCs are presented as follows.

The Human Resource category includes aspects that are quantitative, such as the number of involved individuals (H1), and qualitative, such as skills and experiences (H2 and H3).

The WF Product category is related to characteristics of physical products that are mostly dealt with during the Construction Execution Phase and Operation and Maintenance Phase. A distinctive feature of job sites is whether heavy equipment is required to move or handle products because of product weight (P2). Difficulty of rework is critical if a WF requires high quality (P3). Potential impact on subsequent WFs is another factor that characterizes WFs (P1). This characteristic, however, is not necessarily limited to physical related WFs.

Time, space (including environmental safety), cost are three major dimensions in construction projects. The most concerning characteristic from each dimension was selected as follows: critical path (T1), spatial coordination (T2), environmental hazard (T5), and high cost (T6). Aspects of each dimension that are characterized by uncertainty are selected because technology advancement may support such aspects by enhancing predictability in a given situation. Lastly, proximity (T4) to human resource is added to this category.

Information and Data category includes seven WFCs. Note that WFs featuring a lot of Information and Data related characteristics are expected to benefit the most from technology. The rapid increase of computing power, storage capacity, and sophisticated software packages are increasingly facilitating diverse demands by end users. Technical standards (I3) and data security (I6) mostly relevant to public sector projects are included in this category. The amount of data updating (I7), data accuracy and uncertainty (I5 and I1) are also important aspects. The diversity of the data format is another challenge in information technology (I4), while seamless data transfer and adequate interpretation among intra-projects is one of the most interesting subjects at the corporate level (I2).

The next category, Management, attempts to identify WFCs from a managerial standpoint. A necessity for specialty organization involvement (M1) and the number of different types of organizations involved (M2) describe intra-organization participation. Communication issues placed should also be included in the management category (M4). Managing a high chance of change (M5) and the primary performance driver associated with quality, safety, cost, and schedule are added to this category (M3).

The final category concerns work procedure. The most obvious characteristics are repetitive activity in physical related WFs and iteration and revision in data intensive WFs (D1 and D4). Procedures driven by regulations, which are mostly regarded as a barrier in implementing new technology, should be included (D3). This category also includes error prone (D2) characteristic as well as complexity of work procedures (D6). Relation to former WFs (D7), and the level of resource usage (D5) are also included in this category.

**Table 5-5: List of Work Function Characteristics by Category**

| **(H) Human Resource** |
| --- |
| H1: Many individuals are involved to perform WF. |
| H2: WF involves many individuals with different skill and specialty. |
| H3: User's, worker's or operator's experience is critical to WF performance. |

| **(P) Work Function Product** |
| --- |
| P1: Performance of subsequent WFs relies heavily on this WF. |
| P2: WF product is large and bulky. |
| P3: Errors are difficult to fix or need a large amount of resources to fix. |

| **(T) Time/Space/Cost** |
| --- |
| T1: WF is a critical path activity in most cases. |
| T2: WF activity requires spatial coordination. |
| T3: WF involves relatively high uncertainty in the following item (cost, schedule, quality, safety). |
| T4: WF management operates in close proximity to workers. |
| T5: WF involves environmental hazard. |
| T6: WF is costly to execute. |

**Table 5-5 (continued)**

| (I) Information & Data |
|---|
| I1: WF involves uncertainty or probabilistic information. |
| I2: Historical data from previous projects are required for execution. |
| I3: WF relies on industry technical standards. |
| I4: WF data are in many different formats. |
| I5: Data accuracy is crucial to successful performance. |
| I6: Security of related data is very important. |
| I7: WF involves significant amount of data updating. |

| (M) Management |
|---|
| M1: A specialty organization is involved in most cases. |
| M2: Many different type of organizations are involved. |
| M3: The primary performance driver of the WF is one of the followings (quality, safety, cost, and schedule). |
| M4: Responsible individual must communicate frequently with others. |
| M5: WF involves high probability of change. |

| (D) Work Procedure |
|---|
| D1: WF involves iterations and revisions. |
| D2: WF is error prone. |
| D3: WF procedures are driven by regulations. |
| D4: WF requires repetitive activity. |
| D5: Some WF resources are often idle. |
| D6: WF procedures are very complex. |
| D7: WF relies on physical output products of many previous WF. |

## 5.4 Work Function Characteristics Selection by Project Phase

A comprehensive list of 31 WFCs has been developed to describe common capital facility WFs for all project phases. Not all WFCs can be applied to every individual WF, because some WFs do not contain certain characteristics. For example, most data intensive WFs do not have the same characteristics as the functions of handling bulk materials or environmental hazards. Excluding weak relations between WF and WFC can minimize tedious responses of “Not Applicable” in data collection process. In search for a methodology of minimizing the number of weak relations, the author found that characteristics of the six project phases could play a differentiating role in grouping individual WFs. Table 5-4 in the previous section displays the relationship between WFC category and project phase. Recollecting phase characteristics and associated WFs, each project phase is correlated with WFCs that can characterize its WFs (Table 5-6).

Table 5-6 shows a trend when grouping characteristics by phase. As described in Table 5-4, Information and Data category WFCs (I1 to I7) are associated with the Front End, Design, Procurement, and Construction Management Phases, which mostly involve data intensive WFs. Management related WFCs appear in the Design, Procurement and Construction Management Phases. Note that the Construction Execution Phase and the Operation and Maintenance Phase, which both involve physical-related WFs, employs WFCs mostly from WF product, human resources, and Time/Space/Cost categories. The Operation and Maintenance Phase shares some characteristics with the Front End because both phases place much responsibility on the owner.

After completing the development of WFCs and matching them by project phase, the survey for the linkage between WFCs and technology demand can be performed. The data collection tool for the assessment the linkage between WFCs and technology demand is designed to measure to what extent a WFC generally suggests that benefits would result from added technology. Technology demand is determined by probable benefits. The greater the benefits expected, the stronger the demand driver a WFC is. Four scaled ordinal values are provided for answer. (Appendix A).

The following section presents data collection results and descriptive analyses of the survey results.

**Table 5-6: Work Function Characteristics of Each Project Phase**

| WFC ID | FE | DS | PR | CM | CE | OM |
|---|---|---|---|---|---|---|
| I1 | x | | X | | | |
| D1 | x | x | x | x | | |
| I2 | x | x | x | | | |
| H1 | x | | x | | | x |
| I3 | x | x | | | | |
| M1 | x | x | | | | |
| I4 | x | x | x | x | | x |
| D2 | x | x | x | x | | x |
| I5 | | x | x | x | | x |
| M2 | | x | x | x | | |
| M3 | | x | x | x | | |
| M4 | | x | x | x | | |
| I6 | | | x | x | | |
| D3 | | | x | x | | |
| T1 | | | x | x | | |
| P1 | | | x | x | | |
| I7 | | | x | x | | |
| D4 | | | | | x | x |
| H2 | | | | | x | x |
| P2 | | | | | x | x |
| P3 | | | | | x | x |
| T2 | | x | | x | x | |
| T3 | | | x | | x | |
| T4 | | x | | x | x | |
| M5 | | x | | x | x | |
| D5 | | | | | x | x |
| D6 | | | | | x | x |
| H3 | | | | | x | x |
| T5 | | | | | x | x |
| T6 | | | | | x | x |
| D7 | | | | | x | x |
| Total | 8 | 13 | 16 | 15 | 14 | 14 |

## 5.5 Work Function Characteristics as Technology Demand Drivers

For the assessment, a total of eight professionals with a strong knowledge of WFCs for a broad scope of WFs were chosen from both industry and academia. A brief introduction to each participant is presented in Table 5-7. The average number of years of the participants' experience in industry or academia is 22 years, which shows considerable experience.

In calculating an average value, one maximum and one minimum values among eight responses were excluded in order to eliminate possible outliers. The average value based on a four-point scale was converted to a ten-point scale for computational consistency. A complete list of data collection results is presented in Appendix C-1.

**Table 5-7: Participant's Professional Background**

| Name | Organization | Years of Experience | Professional background |
|---|---|---|---|
| Mike Markovich | Ontario Power Generation | 33 | senior project resources manager in utility industry |
| John Rickard | Pi Architects & Engineers | 23 | registered both as architect and engineer; principal of a consulting firm |
| Carl Haas | Univ. of Texas at Austin<br>Dept. of Civil Eng. | 11 | academic with specialty in construction automation |
| Richard Tucker | Univ. of Texas at Austin<br>Dept. of Civil Eng. | 40 | senior academic with broad project management interests |
| Steve Thomas | CII | 9 | adjunct academic with specialty in industry metrics |
| Delbert Tesar | Univ. of Texas at Austin<br>Dept. of Mechanical Eng. | 40 | senior academic with specialty in manufacturing automation |
| Suzanne Barbber | Univ. of Texas at Austin<br>Dept. of Electrical Eng. | 9 | academic with specialty in software engineering and consulting |
| Doug Morrice | Univ. of Texas at Austin<br>Dept. of Mgmt Science and Information Systems | 11 | academic with background in corporate management, organizations, and operations research |

### 5.5.1 Data Collection Results and Analysis

Table 5-8 lists the data collection results that indicate to what degree a WFC serves as a technology demand driver potential. On a ten-point scale, the results range from 3.89 to 9.44 with an average of 6.34. On an absolute scale, no WFC is classified at a *low* level (between 0.00 to 3.33). Sixteen out of 37 expanded list are assessed as high demand potential (between 6.67 to 10.00).

The survey shows that the WFC with the greatest demand potential for technology involves the need for historical data from previous projects (I2). WFs involving this characteristic include project initialization based on previous similar projects, reaching a bidding decision with the company's bid history, estimating by use of an accumulated unit cost database, extracting data on the subcontractors' performance, and referring any accumulated knowledge to the corporate level. The five WFCs with the highest demand potential are associated with either Data and Information aspects (I2, I7, and I5) or repetitive or iterative procedures (D1 and D4). Six out of seven WFCs in the Data and Information aspect category fall into *high* level in an absolute scale. These results clearly suggest that a well-structured database system and technology replacing human's repetitive actions should be the most beneficial tool.

On the other hand, WF management in close proximity to workers (T4), such as supervising, dynamically coordinating, and directing workers is assessed as the weakest potential driving technology demand. Specialty organization involvement is ranked the least as well (M1). This characteristic involves less market demand due to its narrow domain. Surprisingly, the heavy equipment related WFC (P2) was ranked at third from the bottom.

In terms of a primary performance driver, schedule and quality indicate stronger technology demand driver potential than cost and safety (M3). Relatively high levels of technology use of the scheduling related WFs (WF1.04, WF 3.06, and WF4.01) throughout the project phases can support this result. Quality not only in data intensive WFs, but also in physical resource related WFs is definitely one of the areas to benefit most from technology advancement. The same sequence (schedule, quality, cost, and safety) is found for performance uncertainty (T3). Among the four main disciplines, safety was assessed as the weakest technology driver. Another safety related WFC (T5) was ranked in the sixth bottom. As a matter of fact, managerial or regulatory processes rather than technology itself have put significant emphases and incentives on safety.

Quantitative aspect of human resource demands a high level of technology (H1), while qualitative aspects (H2 and H3) show relative weakness as technology demand driver potential. Replacement or partial substitution of human skills and experiences is still challenging to technology developers.

Regulation driven WFs (D3) and data security (I6) do not show a high level of technology demand.

**Table 5-8: Survey Results of Work Function Characteristics as Technology Demand Driver Potential**

| ID | Work Function Characteristics | Technology Demand Driver Potential Score |
|---|---|---|
| I2 | Historical data from previous projects are required for execution. | 9.44 |
| I7 | WF involves significant amount of data updating. | 8.89 |
| D1 | WF involves iterations and revisions. | 8.33 |
| D4 | WF involves repetitive activity. | 8.33 |
| I5 | Data accuracy is crucial to successful WF performance. | 7.78 |
| M3 | *Schedule* is the primary performance driver to WF. | 7.78 |
| M3 | *Quality* is the primary performance driver to WF. | 7.78 |
| T2 | WF activity requires spatial coordination. | 7.78 |
| I4 | WF data are in many different formats. | 7.78 |
| H1 | Many individuals are involved to perform WF. | 7.22 |
| M4 | Responsible individual for WF must communicate frequently with others. | 7.22 |
| I1 | WF involves a lot of uncertainty or probabilistic information. | 7.22 |
| M2 | Several different organizations are involved in WF. | 6.67 |
| T1 | WF is a critical path activity in most cases. | 6.67 |
| D6 | WF procedures are very complex. | 6.67 |
| I3 | WF relies on industry technical standards. | 6.67 |
| T3 | WF involves relatively high uncertainty in *schedule* performance. | 6.39 |
| T6 | WF is costly to execute. | 6.11 |
| P1 | Performance of many subsequent WFs relies heavily on this WF. | 6.11 |

**Table 5.8 (continued)**

| ID | Work Function Characteristics | Technology Demand Driver Potential Score |
|---|---|---|
| D2 | WF is error prone. | 6.11 |
| D3 | WF procedures are driven by regulations. | 6.11 |
| T3 | WF involves relatively high uncertainty in *quality* performance. | 5.83 |
| T3 | WF involves relatively high uncertainty in *cost* performance. | 5.83 |
| M3 | *Cost* is the primary performance driver to WF. | 5.56 |
| I6 | Security of related data is very important. | 5.56 |
| P3 | Errors are difficult to fix or require a large amount of resources to fix. | 5.56 |
| M5 | WF involves high probability of change. | 5.56 |
| D5 | Some WF resources are often idle. | 5.56 |
| M3 | *Safety* is the primary performance driver to WF. | 5.56 |
| H2 | WF involves many individuals with different skills and specialties. | 5.00 |
| H3 | User’s, worker's, or operator's experience is critical to performance. | 5.00 |
| T5 | WF involves environmental hazard. | 5.00 |
| D7 | WF relies on or requires physical output products of many previous WF. | 5.00 |
| T3 | WF involves relatively high uncertainty in *safety* performance. | 4.72 |
| P2 | WF product is physically large and bulky. | 4.00 |
| M1 | A specialty organization is involved in most cases. | 3.89 |
| T4 | WF management operates in close proximity to workers. | 3.89 |

### 5.5.2 Data Analysis by Work Function Characteristic Category and Project Phase

Figure 5-2 displays the overall levels of WFC as technology demand driver potential grouped by the six WFC categories. Three categories, Human Resource, WF Product, and Time/Space/Cost, which were chosen mostly to characterize the physical related WFs, show lower values than the overall average, 6.34. The category of Information and Data exhibits the most WFC technology demand driver potential. This result supports the common sense that data intensive WFs are more technology demanding than other WFs. Management factors and WF Procedures also show higher demand values than the average.

Another grouping of the WFCs is possible by the project phase**.** Figure 5-3 shows a distinctive difference from Phases 1 to 4 and 5 to 6. This can also be explained in a similar way because Phase 5 and 6 involve many WFCs from the category of Human Resource, WF Product, and Time/Space/Cost. Figure 5-3 also shows a slight bias in WFC toward IT rather than physical entities.

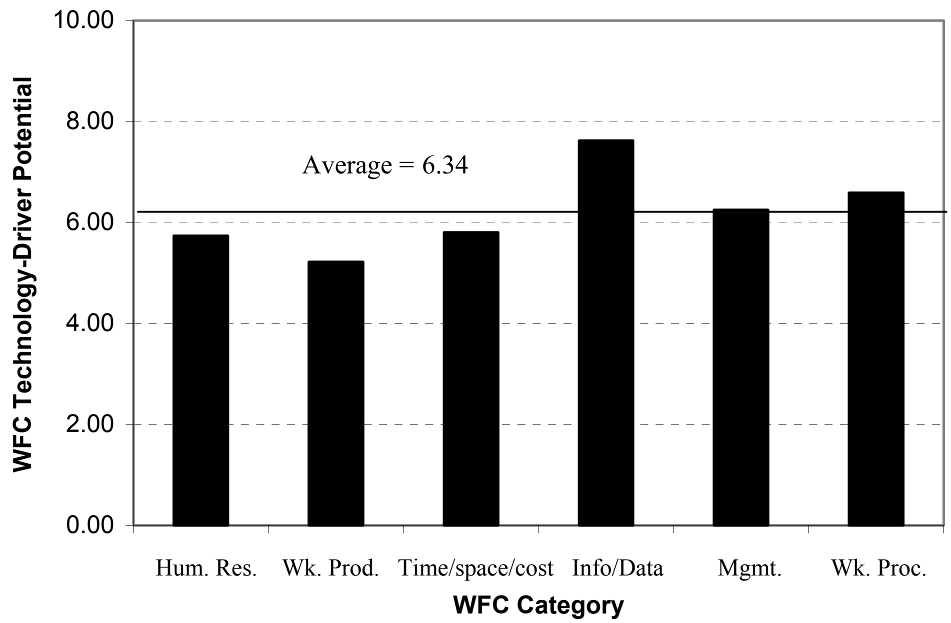



**Figure 5-2: WFC Technology Demand Driver Potential by Category**

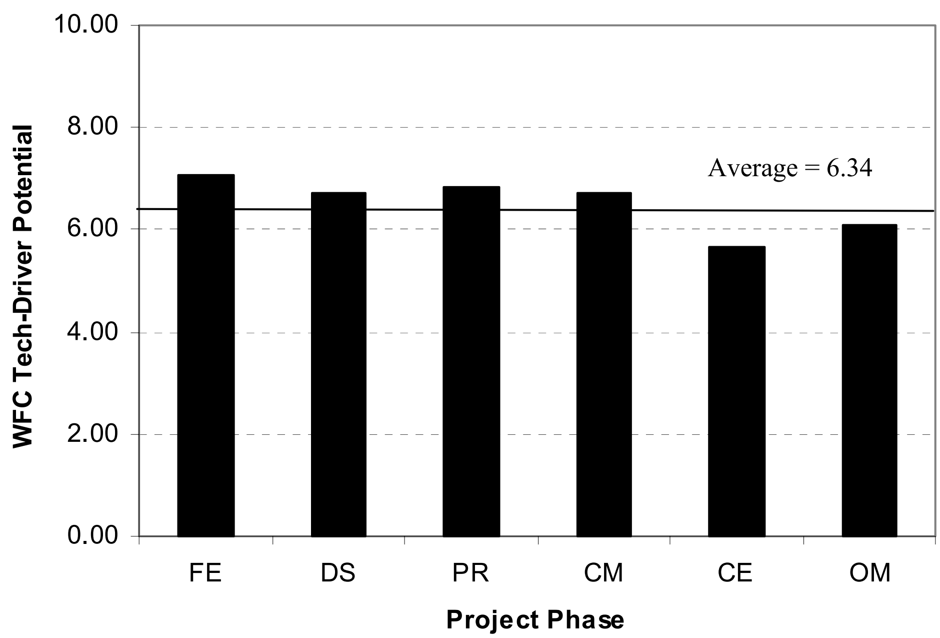



**Figure 5-3: WFC Technology Demand Driver Potential by Project Phase**

# CHAPTER 6 RESEARCH PROOF MODEL

## 6.1 Introduction

The purpose of the Proof Model is to prove the research hypothesis regarding the value of WFCs as technology demand drivers. Independent assessments from the Technology Demand Model and the Technology Supply Model produce the level of technology use as stated in Assumption #1. This technology use is assessed by the hypothesized relationship between WFCs and technology demand. For the validation of the hypothesis based technology use level, the Proof Model compares the hypothesis based technology use level with the surveyed technology use level (Figure 6-1).

This chapter consists of four major parts: 1) Development of the Research Proof Model and WF selection, 2) development of the Technology Demand Model and data collection results, 3) development of the Technology Supply Model and data collection results, and 4) proof of the research hypothesis.

## 6.2 Model Development

The Proof Model starts with a reasonable number of WFs. With the selected WFs, both the Technology Demand Model and the Technology Supply Model should be involved, and these models generate the Demand Index and Supply Index of each

WF. By taking the lower value between the two indices, the hypothesis based technology use level is obtained. This procedure applies to all the selected WFs.

Correlation analysis is suggested for a proper statistical analysis to compare two sets of data. This analysis statistically suggests how strongly the hypothesis based technology use levels are related to the surveyed ones.

A detailed description of the data collection methodology, including the choice WFs and the participant selection procedure, is presented in the next section.

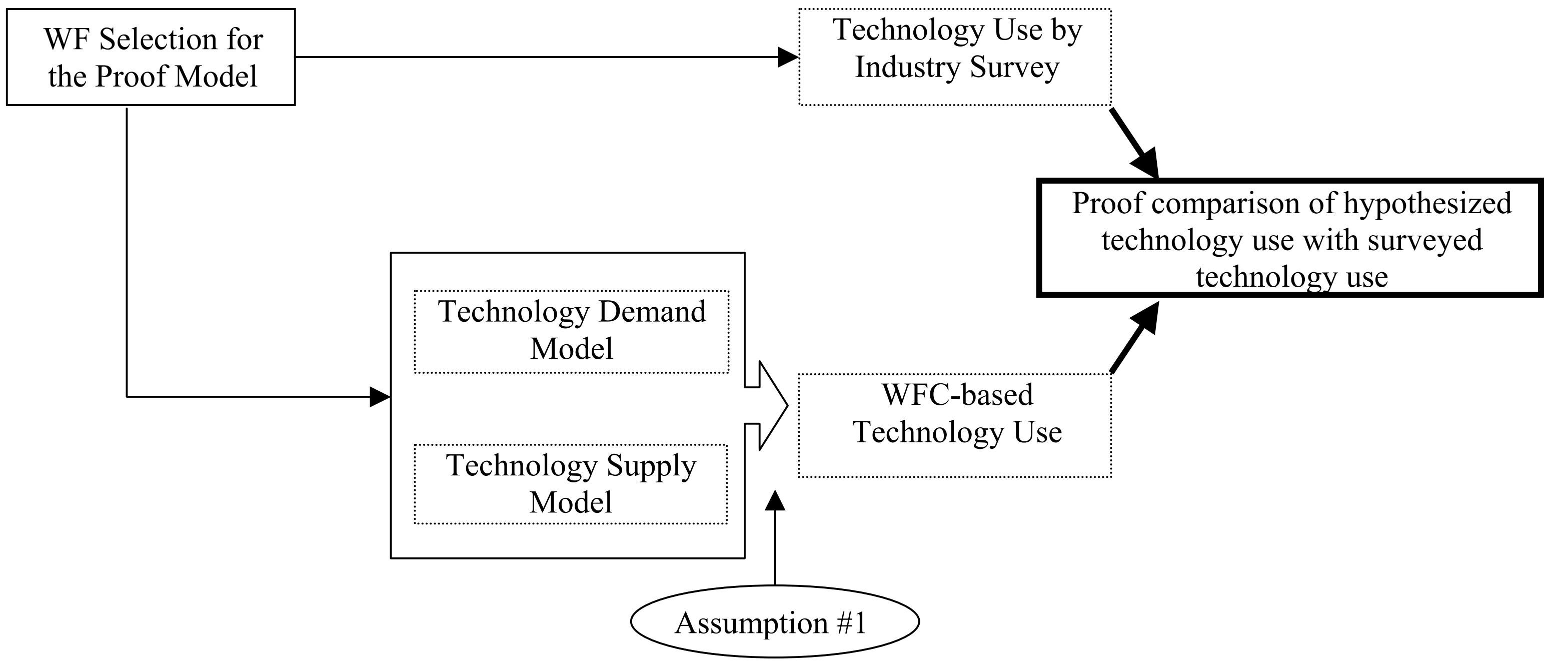



**Figure 6-1: Research Proof Model**

## 6.3 Selection of WFs and Participants for the Research Proof Model

As described in the previous section, the Proof Model starts with the selection of WFs for the hypothesis test. The question is how many and which WFs should be selected for the Proof Model to be robust.

In order to represent characteristics of capital facility projects overall, the following criteria were developed before selecting WFs:

- Involvement of three levels of technology use (high, medium, and low).
- Relatively small standard deviation meaning less variation by project type or characteristics.
- Selection from all six project phases.
- Involvement of owner, A/E, and GC responsible WFs.
- Relatively stable technology to minimize possible difference by time elapse between IA Metrics survey and current survey.

Twelve WFs out of 68 WFs satisfying the above criteria were selected; seven WFs in low use, four WFs in medium use, and one WF in high use. The sample size seems to be small, but it is 17.6% of the total data sets. Responsible organization, owner, A/E, and GC is another major factor to select twelve WFs. Participants for the survey of WF characterization were asked to assess the WFs responsible by their organization. Three WFs for A/E, seven WFs for GC, and three WFs for owner, with one WF overlap, were selected. Table 6-1 lists the twelve selected WFs and their properties.

**Table 6-1: Selected Work Functions for the Proof Model**

| ID | Work Function | Tech. Usage | | Responsible Org. | Tech. Supply Stability |
|---|---|---|---|---|---|
| | | Mean | Std. Dev. | | |
| 5.03 | Construct rebar cages | 1.43 | 2.42 | GC | Stable |
| 5.08 | Manipulate and hang sheet rock | 1.45 | 2.46 | GC | Stable |
| 2.02 | Get input from builders and suppliers regarding construction methods selection and sequence | 2.17 | 2.90 | AE | Moderate |
| 5.11 | Apply paint or coating | 2.28 | 2.57 | GC | Moderate |
| 3.01 | Determine the lead time required to order equipment and materials | 2.33 | 3.10 | Owner/GC | Stable |
| 4.06 | Track the inventory of materials on site | 2.62 | 3.36 | GC | Moderate |
| 6.03 | Use as-built information in personnel training | 2.99 | 3.25 | Owner | Moderate |
| 5.02 | Carry out earthwork and grading | 4.94 | 2.30 | GC | Slightly |
| 4.04 | Update the current cost forecast | 5.29 | 3.13 | GC | Moderate |
| 1.05 | Develop a milestone schedule from the scope of work | 5.62 | 2.86 | Owner | Stable |
| 2.07 | Design the structural systems and related drawings | 6.39 | 3.12 | AE | Slightly |
| 2.05 | Generate facility floor plans | 6.70 | 3.18 | AE | Moderate |

Given the selected WFs, specialized professionals and experienced in executing real work tasks were selected. The survey drew on the expertise of a total of 17 industry professionals. Table 6-2 presents the numbers of participants by organization type and industry sector. As intended, participants were selected without a large skew toward a particular group, and there were slightly more participants in the owner and GC groups as well as in the building sector. Participants were recommended by Dr. James T. O'Connor.

**Table 6-2: Summary of Participants for Characterizing Work Functions**

| Organization Type | Owner | A/E | GC | Total |
|---|---|---|---|---|
| Participants | 7 | 4 | 6 | 17 |
| Industry Sector* | Building | Infrastructure | Industrial | Total |
| Participants | 8 | 4 | 6 | 17 |

*: allowed multiple choices

## 6.4 Technology Demand Model

### 6.4.1 Model Development

It is rational to expect that the relative demand for technology associated with a particular project WF is, at least in part, driven or established by particular characteristics of the WF. The purpose of the Technology Demand Model is to assess the technology demand of an individual WF by means of WFCs. Instead of assessing the technology demand of each WF directly, the model employs WFCs as a bridge between WFs and technology demand (Figure 6-2). Two different types of assessments are required: (1) the extent of linkage between WFCs and technology demand, and (2) characterization of individual WFs.

The data collection results from the first assessment were presented in Chapter 5. The second assessment characterizes an individual WF by a list of probable characteristics. WFs in the same phase are provided with the same list of characteristics as shown in Table 5-6. However, the degree to which the WFCs apply to each WF varies. Therefore, an individual WF can be weighted uniquely by a series of WFCs.

The technology demand of an individual WF via WFCs can be determined by calculating the average value of the product summation of the degree of WFCs to the WF and the degree of the corresponding WFCs to technology demand. Technology Demand Index of $WF_i$ ($\mathbf{D}_i$) can be expressed as

$$\mathbf{D}_i = \frac{\sum_{j=1}^{k} W_{ij} R_{ij}}{10 \cdot k} \qquad (\textit{Equation 1})$$

where $W_{ij}$ is the degree of WFCs to technology demand related $WF_i$; $R_{ij}$ is the degree of WFCs to $WF_i$; $K$ is the number of WFCs applied to WF$i$; 10 is for converting to 0 to 10 scale

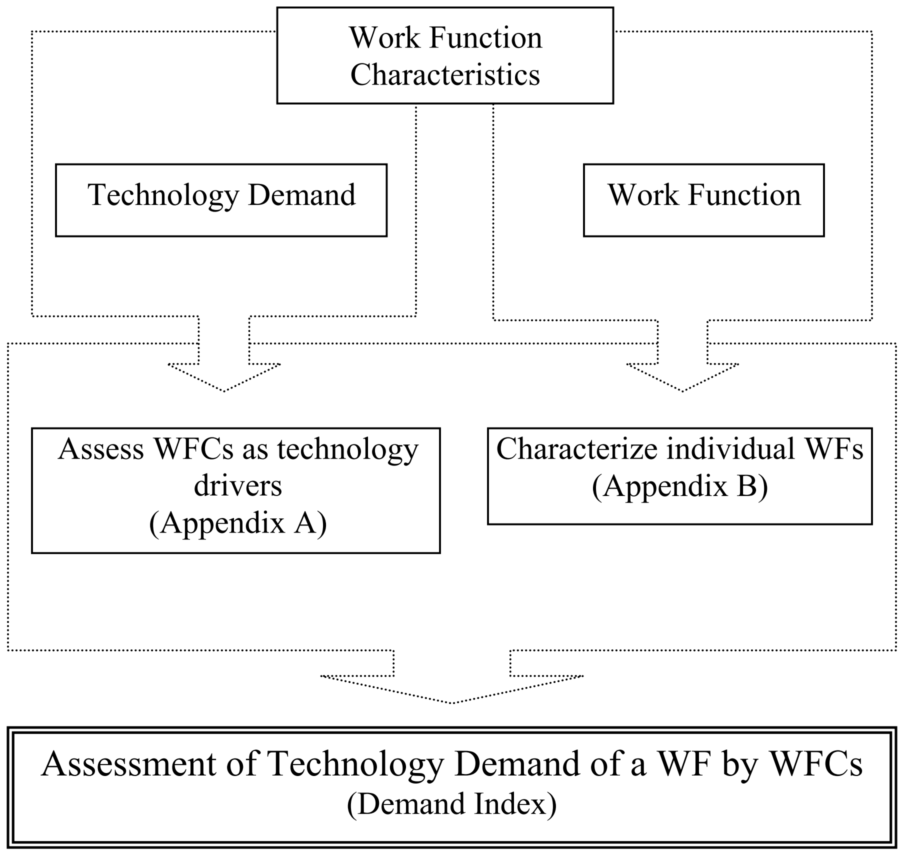



**Figure 6-2: Technology Demand Model**

### 6.4.2 Characterization of Work Function

The survey for the characterization of individual WFs reveals how strongly a WF retains certain features. Figure 6-3 illustrates the degree of technology demand of a WF based on WFCs in an $x$-$y$ plane. A series of WFC data, of which the $x$ value is the degree to which it apply to a particular WF, and the $y$ value is the general degree of technology demand driver potential, is dotted on the plane for each WF. A point can move horizontally according to the degree to the relationship with a WF.

However, its vertical position representing its general degree to technology demand driver potential cannot be altered, no matter which WF it relates to. The farther to the right a data point is located, the more strongly a WF can be explained by the WFC. Likewise, the higher a point is located, the stronger the WFC drive technology demand. By combining those two values in an *x-y* plane, we can observe at a glance the degree to which technology demand is explained by WFCs for an individual WF. If the data points are collected in the upper right corner, then the demand is strongly driven by the WFCs. Note that if a data point is located at the lower left corner, where both degrees are low, it does not generate weak demand to a WF. Rather, the point is "Not Applicable."

Figures 6-4 to 6-15 display the data sets representing the WFCs-based technology demand for each WF selected for the Research Proof Model. They clearly illustrate that each WF, and even WFs in the same phase, has a unique combination of characteristics. The data collection tool was designed to include a minimum number of "Not Applicable" situations by putting together shared phase characteristics; nevertheless, several assessments show weak relationships. About half of WFCs assigned to WF5.03, WF5.08, and WF5.11 characterize the WFs weakly. This may reflect that WFs in the Construction Execution Phase exhibit more diversity and share fewer common features.

On the other hand, some WFCs show a perfect relationship with certain WFs. WF2.02 necessarily involves several different organizations, and there is a complete agreement that quality is the primary driver in performing WF2.07. WF4.04 is obviously a cost performance oriented WF. Two WFs from the Construction Execution Phase, WF5.08 and WF5.11, are responses concern for quality variation. It is readily seen that the data points for all of the five WFs belonging to the Construction Execution Phase and Operation and Maintenance Phase are plotted at a relatively lower zone than other WFs.

Table 6-3 summarizes the data set used to plot Figure 6-4 to Figure 6-15. Solid boxes indicate high degree applicability between the WFCs and the WF. Points with a value of zero are eliminated, because they are regarded as “Not Applicable.” With the point data sets, the Technology Demand Index of individual WFs calculated by *Equation 1* is presented in the following section.

| Technology demand driver potential \ Applicability of WFCs | Low | Medium | High |
|---|---|---|---|
| High | Weak demand | Strong demand | Very strong demand |
| Medium | Very weak demand | Medium | Strong demand |
| Low | Not applicable | Very weak demand | Weak demand |

**Figure 6-3: Degrees Affecting Technology Demand of a WF by WFC**

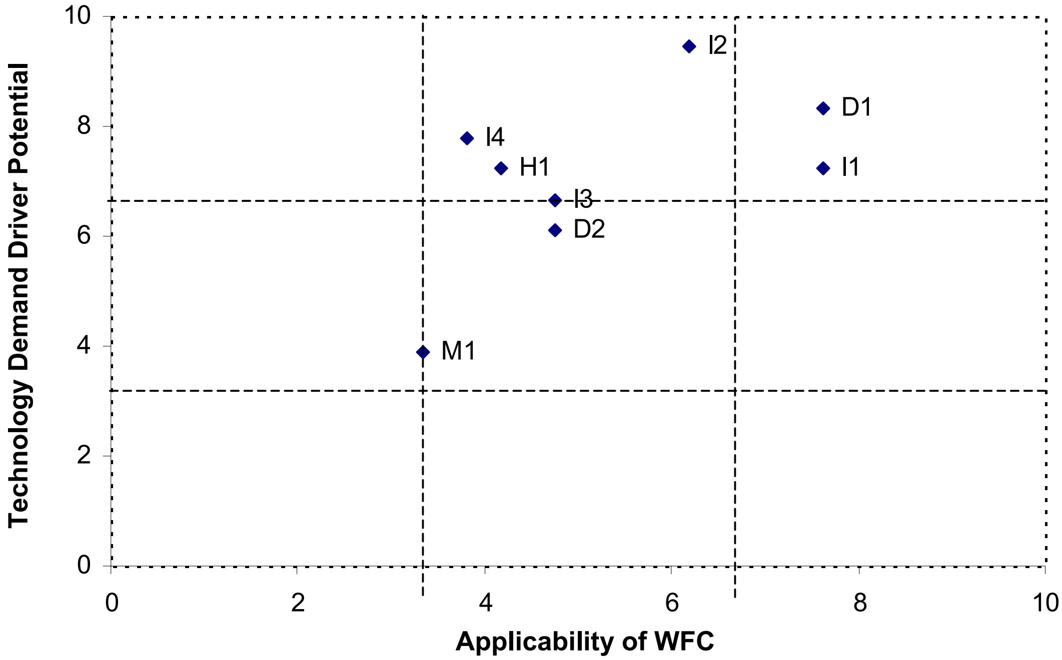



**Figure 6-4: Characterization of WF1.05 (Prepare Milestone Schedule)**

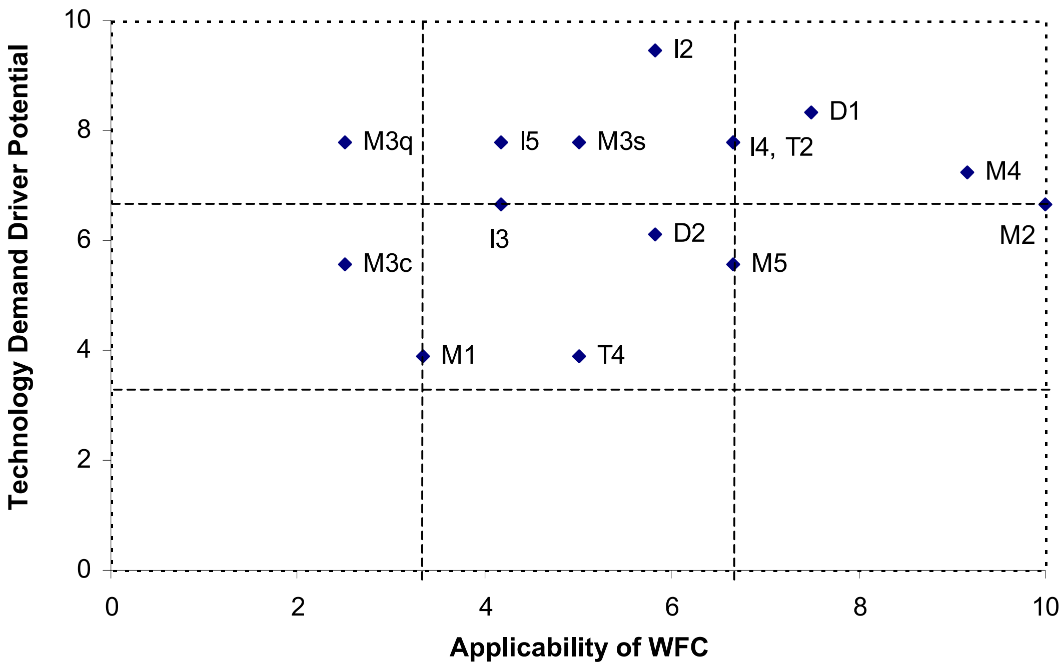



**Figure 6-5: Characterization of WF2.02 (Field Input on Construction Methods and Sequencing)**

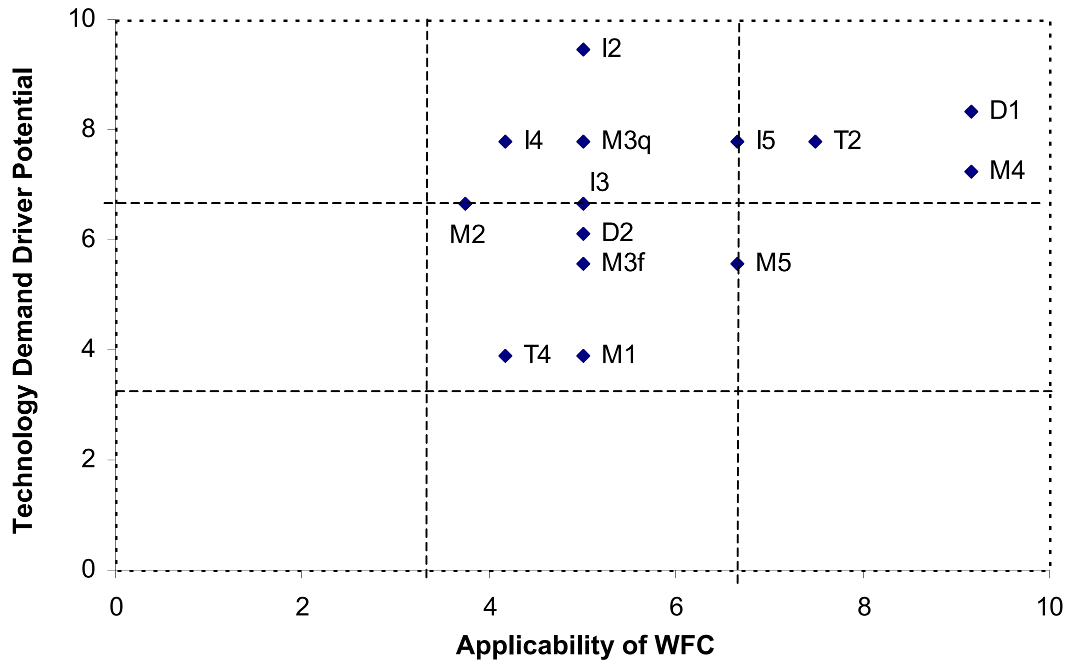



**Figure 6-6: Characterization of WF2.05 (Prepare Floor Plans)**

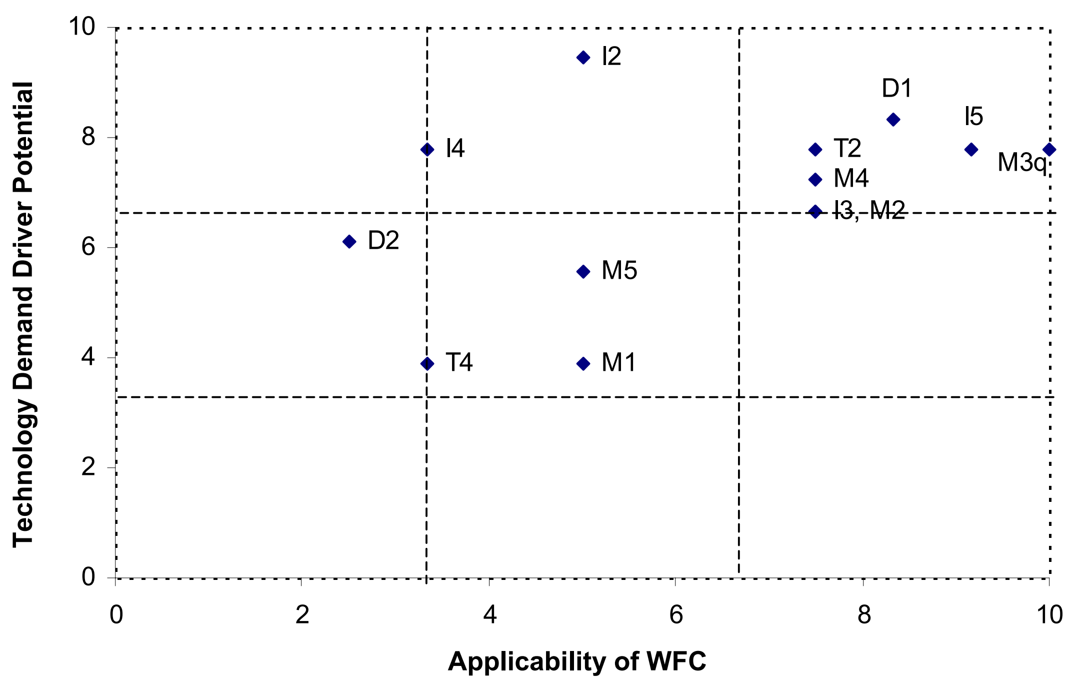



**Figure 6-7: Characterization of WF2.07 (Design Structural Systems)**

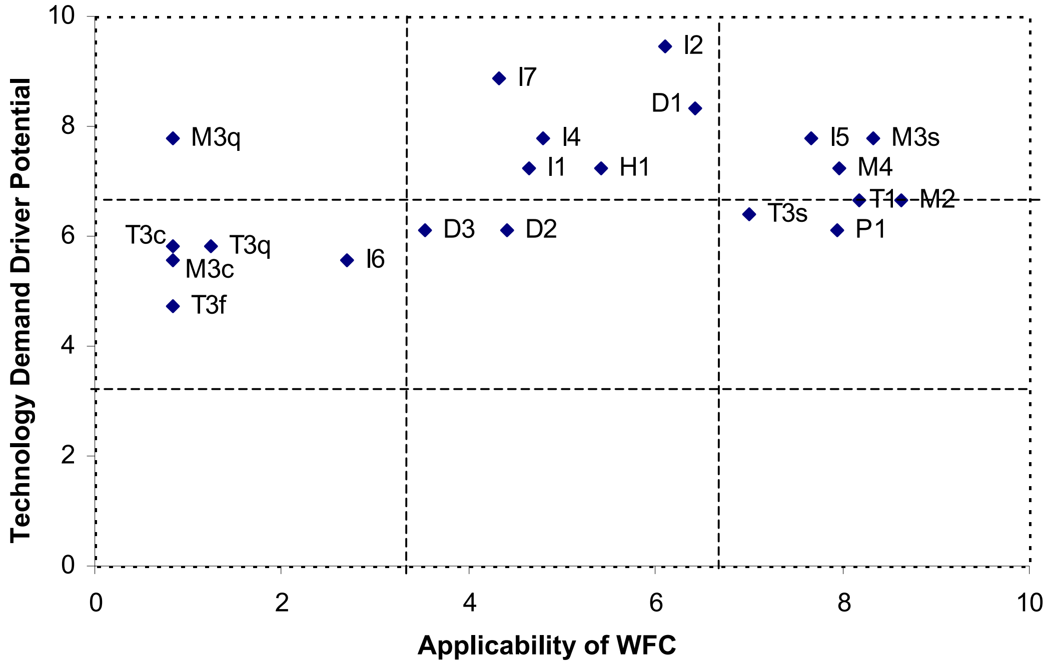



Figure 6-8: Characterization of WF3.01 (Determine Procurement Lead Times)

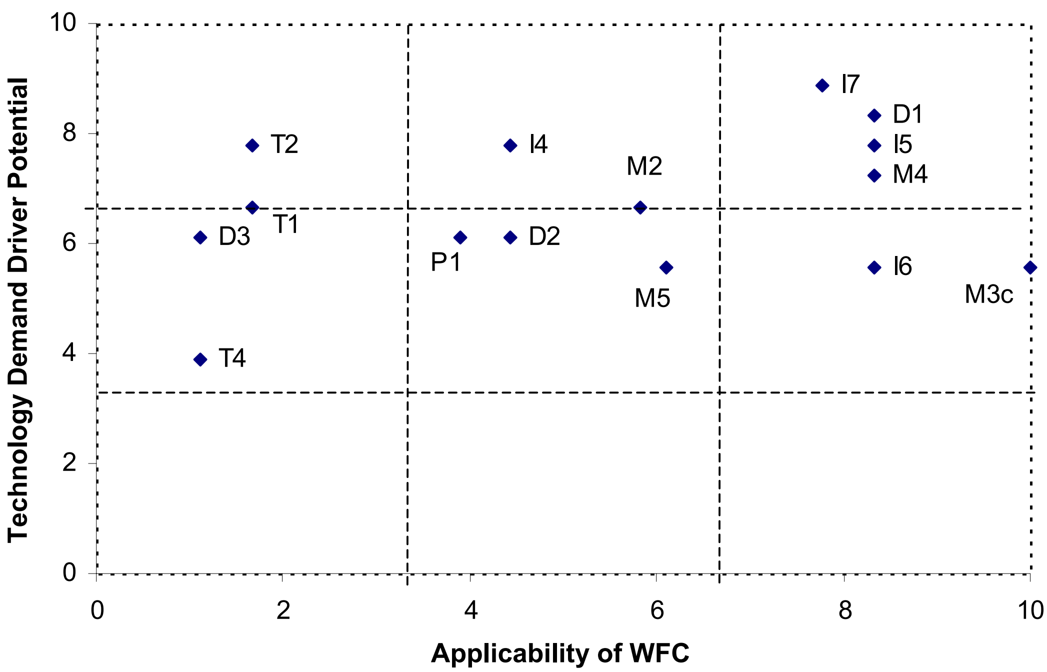



Figure 6-9: Characterization of WF4.04 (Update Cost Forecast)

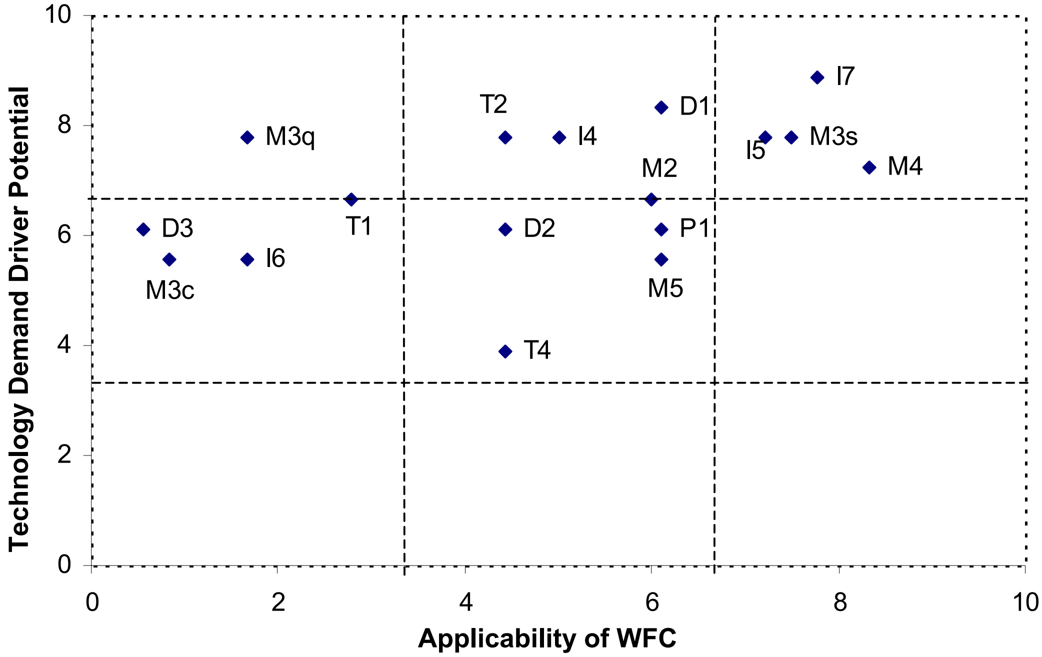



**Figure 6-10: Characterization of WF4.06 (Track On-site Material Inventory)**

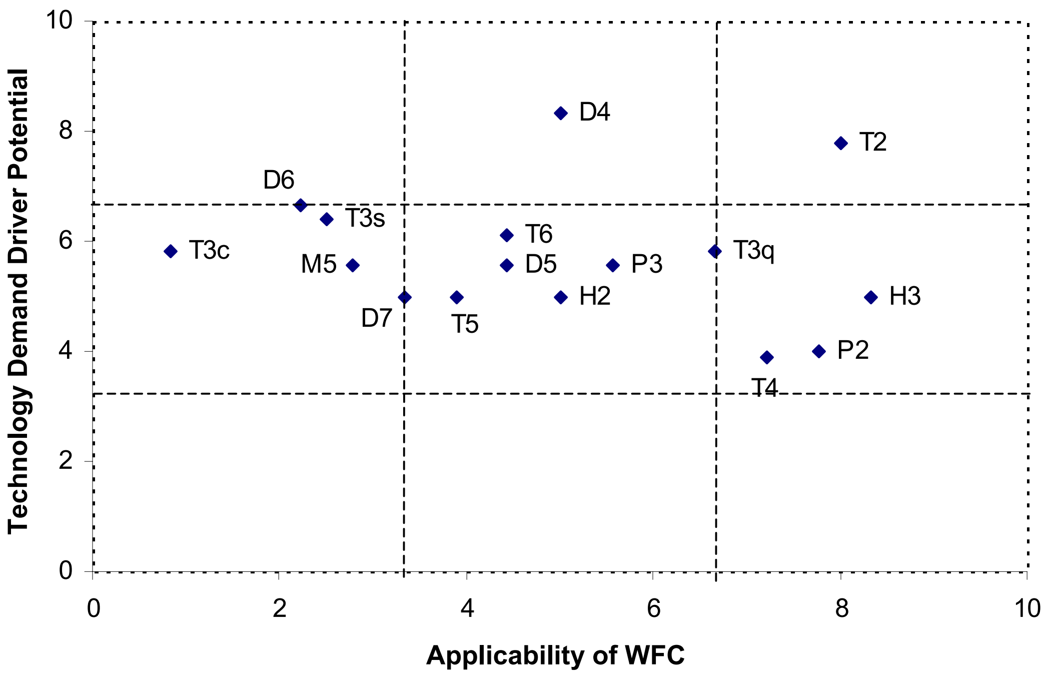



**Figure 6-11: Characterization of WF5.02 (Earthwork and Grading)**

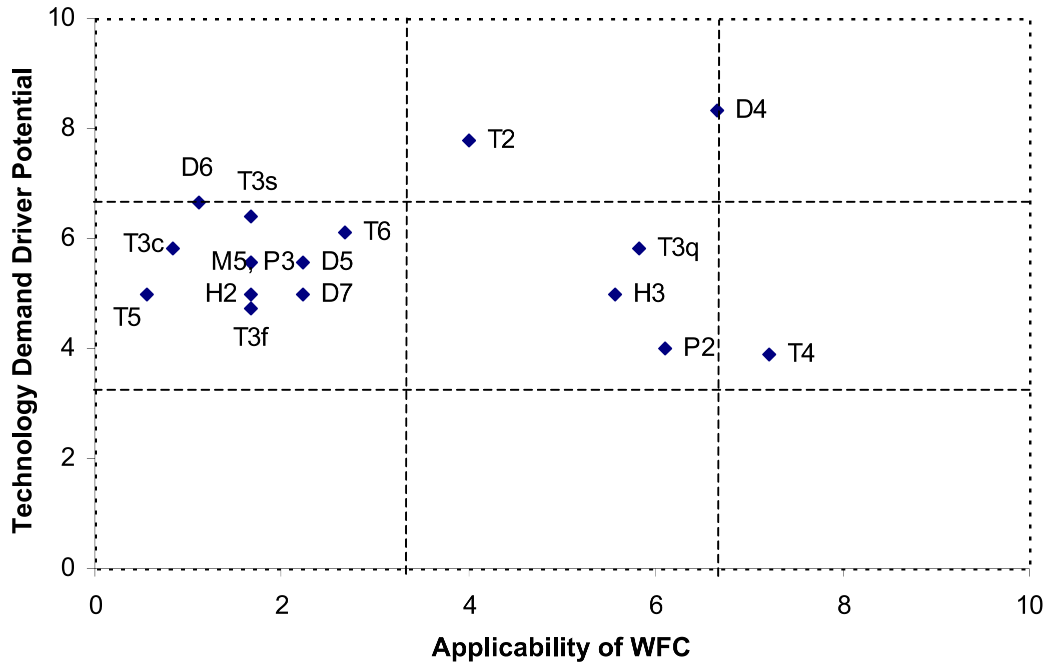



**Figure 6-12: Characterization of WF5.03 (Fabricate Rebar Cage)**

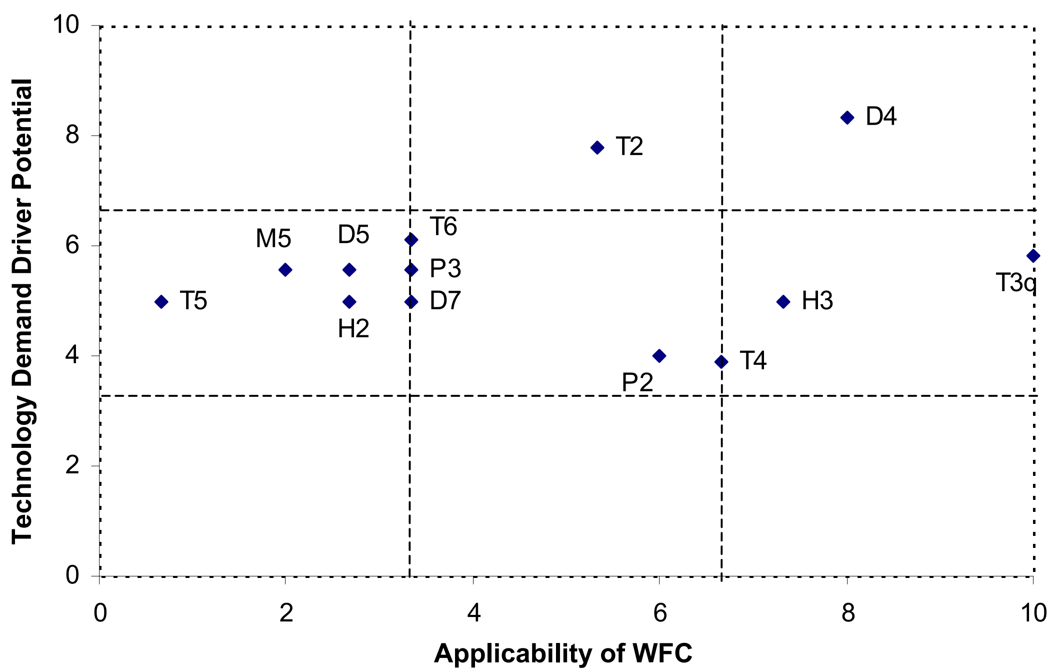



**Figure 6-13: Characterization of WF5.08 (Manipulate/Hang Sheet Rock)**

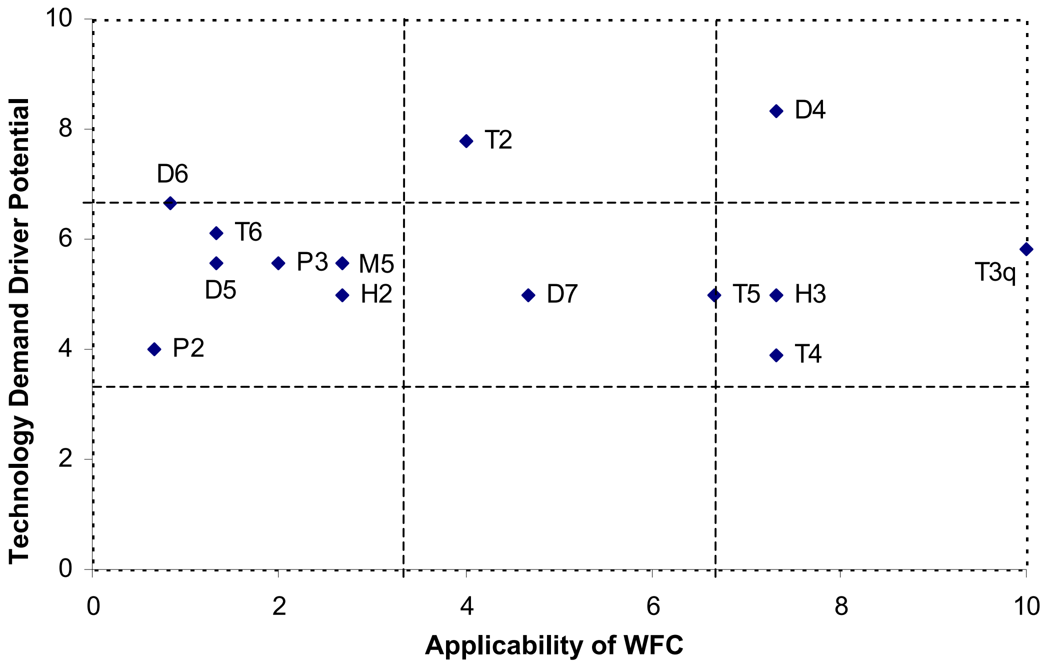



**Figure 6-14: Characterization of WF5.11 (Apply Paint and Coating)**

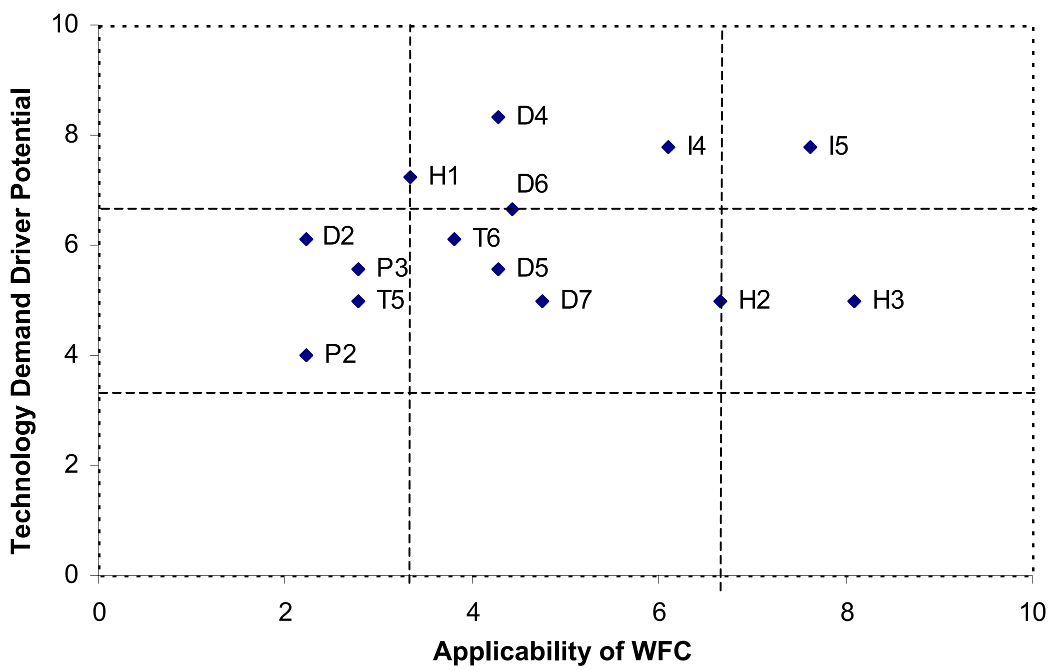



**Figure 6-15: Characterization of WF6.03 (Use As-Built Information in Operator Training)**

**Table 6-3: Response Scores for Characterization of Selected Work Functions – Research Proof Model**

| WFC ID | 1.05 | 2.02 | 2.05 | 2.07 | 3.01 | 4.04 | 4.06 | 5.02 | 5.03 | 5.08 | 5.11 | 6.03 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I1 | 7.62 | | | | 4.64 | | | | | | | |
| D1 | 7.62 | 7.50 | 9.17 | 8.33 | 6.43 | 8.33 | 6.11 | | | | | |
| I2 | 6.19 | 5.83 | 5.00 | 5.00 | 6.11 | | | | | | | |
| H1 | 4.17 | | | | 5.42 | | | | | | | 3.33 |
| I3 | 4.76 | 4.17 | 5.00 | 7.50 | | | | | | | | |
| M1 | 3.33 | 3.33 | 5.00 | 5.00 | | | | | | | | |
| I4 | 3.81 | 6.67 | 4.17 | 3.33 | 4.80 | 4.44 | 5.00 | | | | | 6.11 |
| D2 | 4.76 | 5.83 | 5.00 | 2.50 | 4.40 | 4.44 | 4.44 | | | | | 2.22 |
| I5 | | 4.17 | 6.67 | 9.17 | 7.66 | 8.33 | 7.22 | | | | | 7.62 |
| M2 | | 10.00 | 3.75 | 7.50 | 8.64 | 5.83 | 6.00 | | | | | |
| M3-Cost | | 2.50 | 0.00 | 0.00 | 0.83 | 10.00 | 0.83 | | | | | |
| M3-Schedule | | 5.00 | 0.00 | 0.00 | 8.33 | 0.00 | 7.50 | | | | | |
| M3-Quality | | 2.50 | 5.00 | 10.00 | 0.83 | 0.00 | 1.67 | | | | | |
| M3-Safety | | 0.00 | 5.00 | 0.00 | 0.00 | 0.00 | 0.00 | | | | | |
| M4 | | 9.17 | 9.17 | 7.50 | 7.98 | 8.33 | 8.33 | | | | | |
| I6 | | | | | 2.70 | 8.33 | 1.67 | | | | | |
| D3 | | | | | 3.53 | 1.11 | 0.56 | | | | | |
| T1 | | | | | 8.17 | 1.67 | 2.78 | | | | | |
| P1 | | | | | 7.94 | 3.89 | 6.11 | | | | | |

**Table 6.3 (continued)**

| WFC ID | 1.05 | 2.02 | 2.05 | 2.07 | 3.01 | 4.04 | 4.06 | 5.02 | 5.03 | 5.08 | 5.11 | 6.03 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I7 | | | | | 4.33 | 7.78 | 7.78 | | | | | |
| D4 | | | | | | | | 5.00 | 6.67 | 8.00 | 7.33 | 4.29 |
| H2 | | | | | | | | 5.00 | 1.67 | 2.67 | 2.67 | 6.67 |
| P2 | | | | | | | | 7.78 | 6.11 | 6.00 | 0.67 | 2.22 |
| P3 | | | | | | | | 5.56 | 1.67 | 3.33 | 2.00 | 2.78 |
| T2 | | 6.67 | 7.50 | 7.50 | | 1.67 | 4.44 | 8.00 | 4.00 | 5.33 | 4.00 | |
| T3-Cost | | | | | 0.83 | | | 0.83 | 0.83 | 0.00 | 0.00 | |
| T3-Schedule | | | | | 7.01 | | | 2.50 | 1.67 | 0.00 | 0.00 | |
| T3-Quality | | | | | 1.25 | | | 6.67 | 5.83 | 10.00 | 10.00 | |
| T3-Safety | | | | | 0.83 | | | 0.00 | 1.67 | 0.00 | 0.00 | |
| T4 | | 5.00 | 4.17 | 3.33 | | 1.11 | 4.44 | 7.22 | 7.22 | 6.67 | 7.33 | |
| M5 | | 6.67 | 6.67 | 5.00 | | 6.11 | 6.11 | 2.78 | 1.67 | 2.00 | 2.67 | |
| D5 | | | | | | | | 4.44 | 2.22 | 2.67 | 1.33 | 4.29 |
| D6 | | | | | | | | 2.22 | 1.11 | 0.00 | 0.83 | 4.44 |
| H3 | | | | | | | | 8.33 | 5.56 | 7.33 | 7.33 | 8.10 |
| T5 | | | | | | | | 3.89 | 0.56 | 0.67 | 6.67 | 2.78 |
| T6 | | | | | | | | 4.44 | 2.67 | 3.33 | 1.33 | 3.81 |
| D7 | | | | | | | | 3.33 | 2.22 | 3.33 | 4.67 | 4.76 |

### 6.4.3 Technology Demand Index

The Technology Demand Index of $WF_i$ ($\mathbf{D}_i$) is calculated by the average value of product summation of the degree of WFCs to the WF ($R_{ij}$) and the degree of the corresponding WFCs to technology demand ($W_{ij}$). In order to keep 0 to 10 scale, the average value is divided by 10. Table 6-4 presents a calculation example of the Demand Index with WF1.05.

**Table 6-4: Example of Demand Index Calculation with WF1.05**

| WFC | Driver factor (A) | Applicability to WF1.05 (B) | A X B |
|---|---|---|---|
| I1 | 7.22 | 7.62 | 55.03 |
| D1 | 8.33 | 7.62 | 63.50 |
| I2 | 9.44 | 6.19 | 58.46 |
| H1 | 7.22 | 4.17 | 30.12 |
| I3 | 6.67 | 4.76 | 31.73 |
| M1 | 3.89 | 3.33 | 12.95 |
| I4 | 7.78 | 3.81 | 29.63 |
| D2 | 6.11 | 4.76 | 29.09 |
| | | *Sum* = | 310.52 |
| | | *K* = | 8 |
| | | Average = 310.52÷8 = | 38.81 |
| | | $\mathbf{D}_i$ = 38.81÷10 = | 3.9 |

Table 6-5 lists the Technology Demand Index of the 12 WF selected for the Research Proof Model in a descending order. The index represents the degree of WFCs-based technology demand. Among 12 WFs, WF2.07 is assessed to involve the most technology demand. Another WF from the Design Phase, WF2.05, follows it. Five WFs from the Construction Execution Phase and Operation and Maintenance Phase show $\mathbf{D}_i$ less than 3.00. WF5.03, construct rebar cage, indicates the lowest value of $\mathbf{D}_i$, 1.77.

**Table 6-5: Technology Demand Index for Selected Work Functions**

| ID | Work Function | $D_i$ |
|---|---|---|
| WF2.07 | Design the structural systems and related drawings | 4.5 |
| WF2.05 | Generate facility floor plans | 4.1 |
| WF1.05 | Develop a milestone schedule from the scope of work | 3.9 |
| WF2.02 | Get input from builders and suppliers regarding construction methods selection and sequence | 3.9 |
| WF4.04 | Track the inventory of materials on site | 3.7 |
| WF3.01 | Determine the lead time required to order equipment and materials | 3.5 |
| WF4.06 | Update the current cost forecast | 3.4 |
| WF6.03 | Use as-built information in personnel training | 2.8 |
| WF5.02 | Carry out earthwork and grading | 2.7 |
| WF5.08 | Manipulate and hang sheet rock | 2.5 |
| WF5.11 | Apply paint or coating | 2.4 |
| WF5.03 | Construct rebar cages | 1.8 |

### 6.4.4 Limitation of Technology Demand Model

Although, the purpose of the demand model in the Research Proof Model is not to associate with technology use, limitations of the Technology Demand Model can be observed by comparing the derived values with actual technology use assessment. According to Assumption #1, the Technology Demand Index is expected to be greater than technology use. However, six out 12 data points conflict with this assumption (Table 6-6). All the five medium or high level WFs (WF1.05, WF2.05, WF2.07, WF4.04, and WF5.02) indicate a large size of error from technology use. This implies that the demand model may have a limitation in assessing technology demand associated with high or medium technology use WFs. Difficulty in generating a high value of technology demand is indicated by the relatively small range of index variation, 2.7, compared with the range of technology uses, 5.27.

One of the reasons for the limitation can be explained by many involvements of weakly related WFCs. Since each WF is assessed by a set of WFCs based on the phase involved, the WF can be assessed by weakly related WFCs. The more the weakly related WFCs involved, the smaller the Technology Demand Index generated. To minimize the limitation from phase grouping, the Technology Demand Index can be calculated with only highly related WFCs, which are shaded in Table 6.3.

Another reason can be found in several underweighted WFCs such as T3, M5, P2, and M1. By increasing the number of survey participants from diverse industry sections, the demand driver potential scores of those WFCs can be more accurate.

**Table 6-6: Comparison Technology Demand Index with Technology Use**

| WF ID | $D_i$ (A) | Tech. Use (B) | Δ (A-B) |
|---|---|---|---|
| **WF1.05** | **3.9** | **5.62** | **-1.7** |
| WF2.02 | **3.9** | 2.17 | 1.7 |
| **WF2.05** | **4.1** | **6.70** | **-2.6** |
| **WF2.07** | **4.5** | **6.39** | **-1.9** |
| WF3.01 | **3.5** | 2.33 | 1.2 |
| **WF4.04** | **3.7** | **5.29** | **-1.6** |
| WF4.06 | **3.4** | 2.62 | 0.8 |
| **WF5.02** | **2.7** | **4.94** | **-2.2** |
| WF5.03 | **1.8** | 1.43 | 0.4 |
| WF5.08 | **2.5** | 1.45 | 1.0 |
| WF5.11 | **2.4** | 2.28 | 0.1 |
| **WF6.03** | **2.8** | **2.99** | **-0.2** |

Bold = conflict by Assumption #1

## 6.5 Technology Supply Model

### 6.5.1 Model Development

The purpose of the Technology Supply Model is to assess the degree of technology supply available for an individual WF. Combining the supply model with the demand model presented in the previous section can provide an evaluation of technology use independent of the IA Metrics survey results.

The flowchart in Figure 6-16 displays the steps in the Technology Supply Model. The model consists of two main parts: 1) development of the assessment system; and 2) supply assessment including actual data collection, assessment, and calculating the Supply Index. The following paragraphs explain the philosophies that guided each step in the development of the assessment system.

For a comprehensive assessment of technology supply from initial research to use by end-users, the study proposes three different levels of technology components: (1) base technologies, (2) technology tools, and (3) tool/system interface standards (Figure 6-17). First, base technologies include fundamental technologies both for current tools and for developing future tools. Second, technology tools include any software and/or hardware products that are used by end-users to perform a WF. Technology tool development is rooted in one or more base or fundamental technologies or sciences. Third, more fully developed technologies involve system interface standards that enable WF linkages.

Each technology component requires its own measurement factors, because each component has a unique set of supply characteristics. The measurement factors should be both general enough and comprehensive enough to deal with various types of technologies required throughout the sequence of project phases. At the same time, the measurement factors should also play a role as differentiator. Table 6-7 lists tool assessment factors for each component. In assessing technology tools, the factors include the number of available tools, market competitiveness; and three qualitative aspects, maturity, functionality, and flexibility. Complexity and maturity are chosen for the assessment of currently applied base technologies, and impact on tools is measured for emerging base technologies. Standard interface is measured by its availability and maturity.

The development of the assessment tool and each factor's scaling system is based upon each assessment factor (Figure 6-18). The assessment tool is developed with simple and clear intervals in order to minimize possible errors from author's rough assessment. The scores of each factor are set as the median value of equally divided intervals in a 0 to 100 scale. For a better representation of supply assessment, each factor was weighted by Dr. James T. O'Connor and confirmed by Dr. Richard L. Tucker. More emphasis is put on tools and standard interfaces than base technologies. These scores and weight values are used to calculate the Supply Index.

In collecting real technology data, the author found a need for a data collection template that should be capable of matching tools and technologies to a

WF under three different technology components. The following section introduces the data collection template and its application to individual WFs.

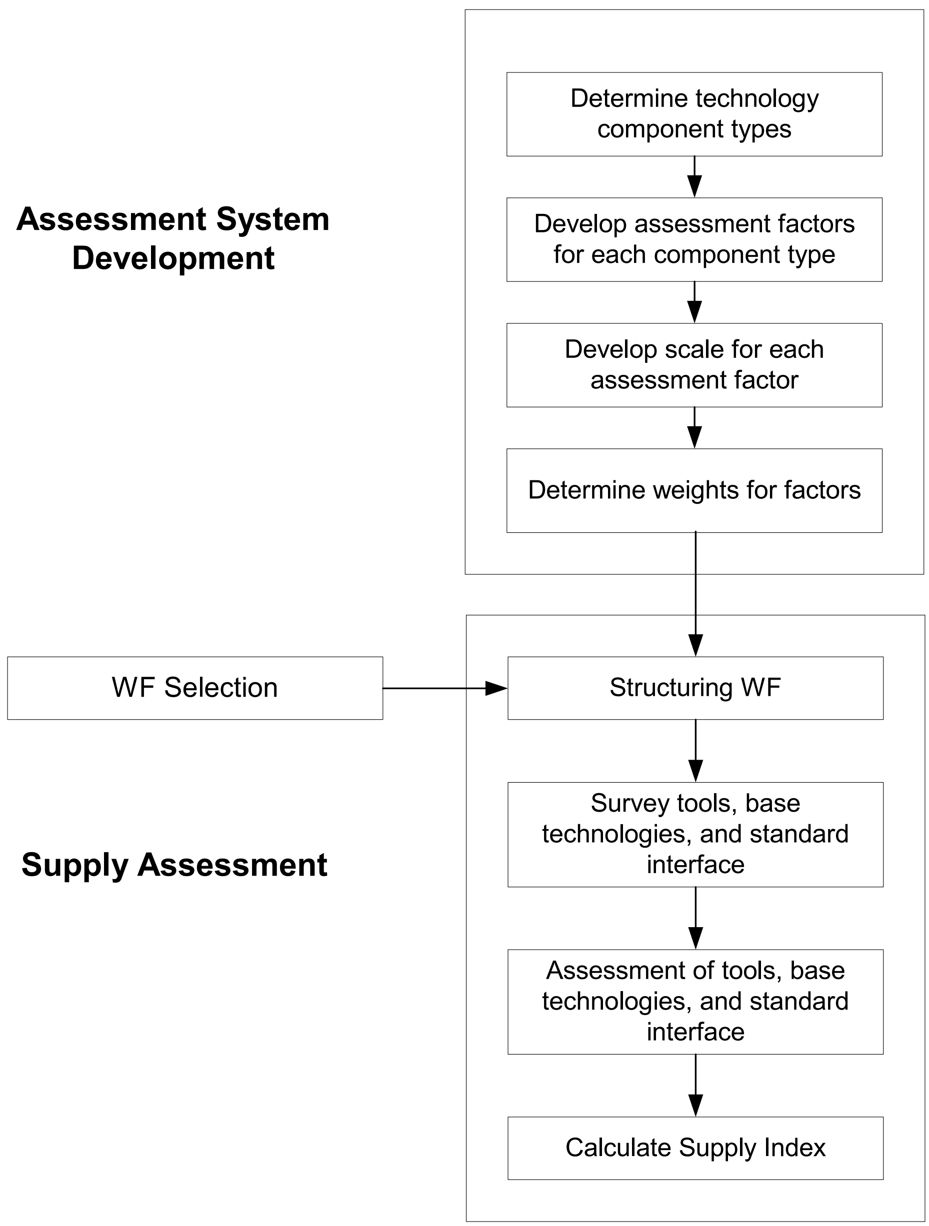



**Figure 6-16: Flowchart for Supply Model Development and Data Collection**

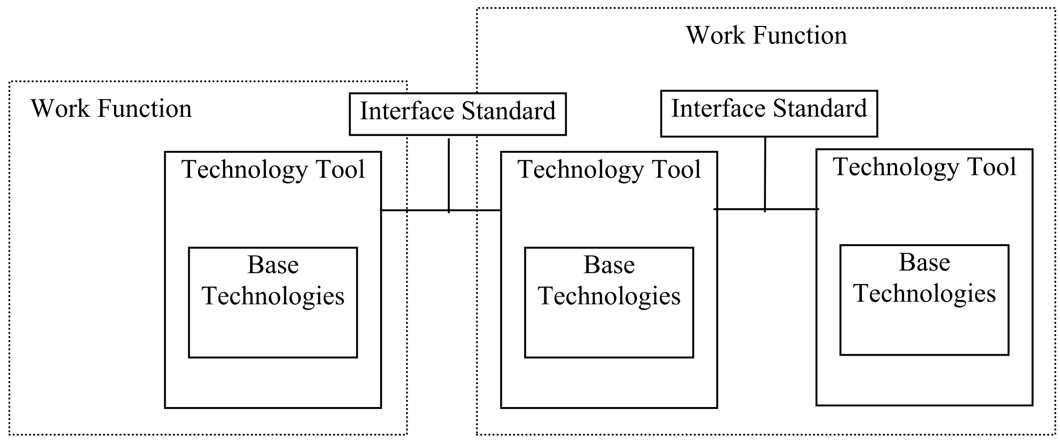



**Figure 6-17: Components of Technology Supply Model**

**Table 6-7: Assessment Factors of Technology Supply Components**

| Tech. Supply Component Type | ID | Assessment Factors | Weight |
|---|---|---|---|
| Technology Tools | T1 | Number of different types of available support technology tools | 5 |
| | T2 | Degree of competition among tool providers | 5 |
| | T3 | Overall maturity of available support technology tools | 10 |
| | T4 | Overall functionality of available support technology tools | 10 |
| | T5 | Overall flexibility/customizability of available support technology tools | 11 |
| Base Technologies | B1 | Degree of complexity or sophistication of base technologies | 6 |
| | B2 | Age and maturity of base technologies | 10 |
| | B3 | Impact on technology tools from emerging base technologies | 10 |
| Standard Interface | I1 | Availability and maturity of multi-system interface system | 34 |

<table>
<tr><th>ID</th><th>Assessment Factor</th><th colspan="60">Degree of Supply with Score</th></tr>
<tr><td></td><td></td><td colspan="15">12.5</td><td colspan="15">37.5</td><td colspan="15">62.5</td><td colspan="15">87.5</td></tr>
<tr><td>T1</td><td>Number of different types of available support technology tools</td><td colspan="15">One or Two</td><td colspan="15">Several but Limited</td><td colspan="15">Diverse</td><td colspan="15">Very Diverse</td></tr>
<tr><td>T2</td><td>Degree of competition among tool providers</td><td colspan="15">Dominated by One or Two Suppliers</td><td colspan="15">Competitive by Limited Suppliers</td><td colspan="15">Competitive</td><td colspan="15">Very Competitive</td></tr>
<tr><td>T3</td><td>Overall maturity of available support technology tools</td><td colspan="15">In Development</td><td colspan="15">Early Application</td><td colspan="15">Proven</td><td colspan="15">Widely Accepted</td></tr>
<tr><td>T4</td><td>Overall functionality of available support technology tools</td><td colspan="15">Very Limited</td><td colspan="15">Limited</td><td colspan="15">Diverse</td><td colspan="15">Very Diverse</td></tr>
<tr><td></td><td></td><td colspan="20">16.5</td><td colspan="20">50</td><td colspan="20">83</td></tr>
<tr><td>T5</td><td>Overall flexibility/customizability of available support technology tools</td><td colspan="20">Inflexible</td><td colspan="20">Somewhat Flexible</td><td colspan="20">Very Flexible</td></tr>
<tr><td>B1</td><td>How complex or sophisticated are related base technologies?</td><td colspan="20">Relatively Simple But Sophisticated</td><td colspan="20">Mix of simple and complex</td><td colspan="20">Relatively Complex & Sophisticated</td></tr>
<tr><td></td><td></td><td colspan="30">25</td><td colspan="30">75</td></tr>
<tr><td rowspan="2">B2</td><td rowspan="2">How would you characterize the base technologies?</td><td colspan="30">mostly old, Out of Date</td><td colspan="30">Mostly Recent, but Proven</td></tr>
<tr><td colspan="30">Experimental, Still in Research Stage</td><td colspan="30">Mostly New, Cutting-Edge, Gaining Acceptance</td></tr>
<tr><td></td><td></td><td colspan="12">10</td><td colspan="12">30</td><td colspan="12">50</td><td colspan="12">70</td><td colspan="12">90</td></tr>
<tr><td>B3</td><td>Tools could be significantly enhanced with emerging base technologies</td><td colspan="12">Strongly Disagree</td><td colspan="12">Disagree</td><td colspan="12">Neutral</td><td colspan="12">Agree</td><td colspan="12">Strongly Agree</td></tr>
<tr><td></td><td></td><td colspan="15">12.5</td><td colspan="15">37.5</td><td colspan="15">62.5</td><td colspan="15">87.5</td></tr>
<tr><td>I1</td><td>Interface standards associated with these tools generally</td><td colspan="15">Don't Exist</td><td colspan="15">Are In Development</td><td colspan="15">Are Partially Supportive</td><td colspan="15">Are Proven & Beneficial</td></tr>
</table>

**Figure 6-18: Conversion of Supply Characteristics to Numerical Values**

### 6.5.2 Structuring of Work Function for Technology Tool

A WF is a functional unit of activity that usually consists of several sub-activities and is supported by a complex array of technologies. WFs and technology tools are rarely a one-to-one match.

Performing a WF that involves several sub-activities usually requires different types of tools for each sub-activity. For example, the WF "construct rebar cage" consists of shearing, bending, tying, and placing. Each sub-activity requires a different type of tool such as a shearing machine, bender, or a tying tool. Some tools involve task-to-task integration features. Physical-related WFs are mostly included in this category.

On the other hand, tools for Data-intensive WFs involve more integration features, and one tool supports several WFs. For example, software tools for schedule or cost control related WFs tend to integrate with project management software and accounting packages.

Therefore, before investigating technology supply, a WF needs to be structured to match the tools provided. Figure 6-19 illustrates two cases: (1) WF decomposition to sub activities requiring different tools, (2) WF as a part of function provided by a package of tools

| **WF: Hang and manipulate sheetrock** | | | | |
|---|---|---|---|---|
| Cutting | Hanging or attaching | Taping & Floating | Filling | Joint finishing |
| Cutting tool | Hanging tool | Taping tool | Filling tool | Finishing tool |

| Cost control software tool with Accounting function | | | | | | |
|---|---|---|---|---|---|---|
| Cost Estimating | Job Cost | **WF: Update the current cost forecast** | Payroll | Purchase Order | Change Order | Invoice |

**Figure 6-19: Structuring Work Function to Match Tools**

### 6.5.3 Assessment of Technology Supply

Assessment of technology supply starts with structuring WFs so as to match available tools. Most physical resource related WFs need to be broken down into sub-activities, while some data intensive WFs are a part of function provided by an integrated software package.

After identifying the WF structure for applicable tools, a tremendous amount of effort were made to search tools, base technologies, and standard interfaces. The results of literature survey on 12 WFs' technology supply are presented in Appendix E. Limited survey resources and time made it impossible to completely examine tools and technologies available. However, it is not practical to survey all the technology supply, nor is this the objective of the supply model. The supply model is aimed to assess an overall technology supply status by supply characteristics. Therefore, the data collections stop when they are good enough to characterize the assessment factors.

### 6.5.4 Technology Supply Data Collection Template

For a systematic survey of tools and technologies, a data collection template was developed. Figure 6-20 illustrates the legend for the template. The template enables the break down of a WF into several sub-tasks; and tools, technologies, or standard interfaces can fill one, two, or several corresponding fields according to their functionality. The template also contains columns for the nearest located WFs, so interface with other entities can be located. Three different entities – organization, phase, and other WF, or any combination of these – can be displayed.

Figure 6-21 shows an example of data collection results using the template. The WF of "construct rebar cage" was broken down into four sub-activities to match tools available in market: bending, shearing, tying, and placing. Most tools available in market supported one of four sub-activities; however, Carel Combo from Ocean Machinery supported two sub-activities: bending and shearing. Data from rebar detailing in the design phase can be interfaced with the WF. Several proprietary robots from Japanese general contractors, which integrate bending, shearing, and tying activities, were investigated. Research for the base technologies of the interface with CAD data was also observed by literature survey.

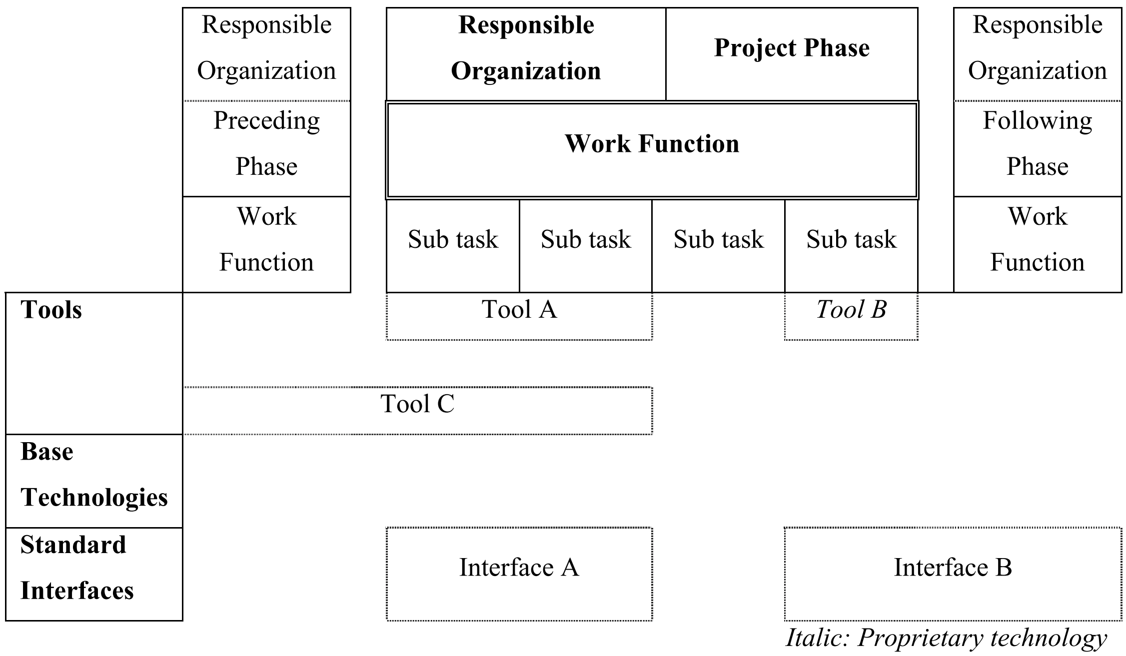



**Figure 6-20: Legend of Technology Supply Data Collection Template**

<table>
<tr><td></td><td>A/E (Design)</td><td colspan="2">GC</td><td colspan="2">Construction</td></tr>
<tr><td></td><td></td><td colspan="4">WF5.03: Construct rebar cages</td></tr>
<tr><td></td><td>Rebar detailing</td><td>Bending</td><td>Shearing</td><td>Tying</td><td>Placing</td></tr>
<tr><td rowspan="3">Tools</td><td>GEOPAK<br>IntelCAD-RC</td><td>PG Benders (GENSCO)<br>STEMA(stirrup bender)<br><br>Rebar bending robot from Obayashi Corp.</td><td>Yard Shears (GENSCO)</td><td rowspan="2">Automatic tying machine</td><td rowspan="3">Automatic rebar placing robot (Japan)</td></tr>
<tr><td></td><td colspan="2">Carell Combo (Ocean Machinery)<br>NC RCB machine</td></tr>
<tr><td></td><td colspan="3">Rebar pre-assemble robot from Shimizu Corp.<br>Automatic fabrication of unit rebar from Takenaka Corp.<br>Reinforcing bar fabricating robot from Taisei Corp.</td></tr>
<tr><td>Base Technologies</td><td>RCCS</td><td>Neural Network</td><td colspan="2"></td><td>Robotic assembly for beams and columns</td></tr>
<tr><td>Standard Interfaces</td><td colspan="3">Interface with CAD</td><td colspan="2"></td></tr>
</table>

**Figure 6-21: Technology Supply Survey on WF5.03**

### 6.5.5 Technology Supply Assessment and Rationalization

This section provides the supply assessments of twelve individual WFs selected for the Research Proof Model. It is felt that data collection efforts have been sufficient for assessing the supply factors. Every assessment factor of each WF is rationalized to support the characterizations of technology supply (Tables 6-8 to 6-19). Scoring of each factor is based on the numbering system presented in Figure 6-18.

The assessment scores are gathered in Table 6-20 for the Supply Index calculation. The Supply Index is a product summation of individual assessment factor multiplied by weights.

**Table 6-8: Technology Supply Assessments (WF1.05)**

| **WF1.05 Develop a milestone schedule from the scope of work** | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Several tools including scheduling or project management software package<br>• Manually scheduling to some degrees | 5 | **37.5** |
| T2 | • Gaining competitiveness between suppliers | 5 | **37.5** |
| T3 | • Start to take advantage of software technology and integrated database technology | 10 | **37.5** |
| T4 | • Currently limited, but Started to provide diverse functionality such as resource planning or detailed time management functionality | 10 | **37.5** |
| T5 | • Can customize to organization fit or flexible to deal with diverse types of capital projects to some degrees | 11 | **50** |
| B1 | • Mostly simply<br>• Moving toward object-oriented programming tools | 6 | **16.5** |
| B2 | • Some proven and old<br>• Some experimental | 10 | **25** |
| B3 | • Web-based technology for more collaborative function | 10 | **50** |
| I1 | • Mostly require to input again manually for next stage | 34 | **37.5** |
| | Supply Index | **3.7** | |

**Table 6-9: Technology Supply Assessment (WF2.02)**

| WF2.02: Get input from builders and suppliers regarding construction methods selection and sequence | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Very limited tools provided | 5 | **12.5** |
| T2 | • Some competitive inputs by builders and suppliers | 5 | **37.5** |
| T3 | • Not mature in prevailing tools | 10 | **12.5** |
| T4 | • Very limited functionality | 10 | **12.5** |
| T5 | • Not flexible | 11 | **16.5** |
| B1 | • Overall simple<br>• Attempt to apply advanced technologies | 6 | **25** |
| B2 | • Mostly old in conventional tools and still in research stage in new technologies | 10 | **25** |
| B3 | • Some visualization tools such as VR and graphical simulation | 10 | **70** |
| I1 | • Don't exist | 34 | **12.5** |
| | Supply Index | **2.2** | |

**Table 6-10: Technology Supply Assessment (WF2.05)**

| WF2.05: Generate floor plans | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Very diverse CAD tools | 5 | **87.5** |
| T2 | • Competitive by leading software companies | 5 | **62.5** |
| T3 | • Widely and mostly accepted tool in design and A/E companies | 10 | **87.5** |
| T4 | • Focused on generating drawings | 10 | **62.5** |
| T5 | • Mostly emphasis on specialty instead of flexibility<br>• Need training personnel | 11 | **50** |
| B1 | • Relatively complex and sophisticated | 6 | **75** |
| B2 | • Mostly proven, but some are still in research stage by academic field | 10 | **75** |
| B3 | • Integration features with other modules<br>• 3D visualization | 10 | **70** |
| I1 | • Need converting process among products<br>• Involving some proprietary information in data file<br>• Efforts to integrate with structural analysis tools and quantity take-off functions | 34 | **62.5** |
| | Supply Index | **6.8** | |

**Table 6-11: Technology Supply Assessment (WF2.07)**

| WF2.07: Design the structural systems and related drawings | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Overall diverse for specialized analysis fields | 5 | **62.5** |
| T2 | • Competitive by specialized suppliers<br>• Developed by in-house research | 5 | **62.5** |
| T3 | • Widely accepted but still need engineering review by professionals | 10 | **62.5** |
| T4 | • Building structure: involving diverse functionality<br>• Infrastructure: specialized for each project | 10 | **50** |
| T5 | • Mostly specialized by industry sector or facility type | 11 | **50** |
| B1 | • Very complex and sophisticated | 6 | **82.5** |
| B2 | • Some proven mathematically (FEM)<br>• Still need engineering check-up | 10 | **75** |
| B3 | • Continuous research in progress | 10 | **70** |
| I1 | • Need data conversion for third party tools<br>• Data compatible among family products | 34 | **62.5** |
| | Supply Index | **6.3** | |

**Table 6-12: Technology Supply Assessment (WF3.01)**

| WF3.01 Determine the lead time required to order equipment and materials | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Mostly in-house tools<br>• Conventional communication tools | 5 | **37.5** |
| T2 | • Mostly in-house development | 5 | **37.5** |
| T3 | • No specific tool widely accepted in industry | 10 | **62.5** |
| T4 | • Simple functionality | 10 | **12.5** |
| T5 | • Not flexible | 11 | **16.5** |
| B1 | • Simple | 6 | **16.5** |
| B2 | • Mostly recent | 10 | **75** |
| B3 | • Beneficial to scheduling function | 10 | **50** |
| I1 | • Emerging B2B technology<br>• Data interface by XML | 34 | **37.5** |
| | Supply Index | **3.9** | |

**Table 6-13: Technology Supply Assessment (WF4.04)**

| **WF4.04: Update the current cost forecast** | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Diverse software for cost controlling but not so diverse in project based and WBS supported cost forecast tools | 5 | **37.5** |
| T2 | • Competitive among software suppliers | 5 | **62.5** |
| T3 | • Widely accepted in corporate-level accounting software<br>• Increasing in construction project cost estimating and control software tools | 10 | **62.5** |
| T4 | • Very diverse functionality as a package tool but less flexibility<br>• Focused on more estimating function<br>• Not as full as functional compared with manufacturing industry | 10 | **62.5** |
| T5 | • Need to customization process<br>• Less functionality but better flexibility<br>• Specialized software by industry type | 11 | **50** |
| B1 | • Programmed by conventional algorithm | 6 | **50** |
| B2 | • Mostly recent software technology and proven | 10 | **75** |
| B3 | • More integrated and collaborative work environment | 10 | **70** |
| I1 | • Limited integration feature for cost forecasting | 34 | **37.5** |
| | Supply Index | **5.3** | |

**Table 6-14: Technology Supply Assessments (WF4.06)**

| **WF4.06: Track the inventory of materials on site** | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Provided by several but limited in types | 5 | **37.5** |
| T2 | • Competitive by limited suppliers | 5 | **37.5** |
| T3 | • Early application in large size projects | 10 | **37.5** |
| T4 | • Getting diversity in combining with tools and material management software | 10 | **37.5** |
| T5 | • Somewhat flexible | 11 | **50** |
| B1 | • Mix of simple and complex | 6 | **50** |
| B2 | • Some in research stage and mostly proven | 10 | **75** |
| B3 | • High chance of improvement of material management from both schedule and cost perspectives | 10 | **90** |
| I1 | • Getting more integration along with material management procedures<br>• Need standard interface with suppliers and sub-contractors | 34 | **62.5** |
| | Supply Index | **5.7** | |

**Table 6-15: Technology Supply Assessment (WF5.02)**

| **WF5.02: Carry out earthworks and grading** | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Diverse equipments by job site condition<br>• Very diverse equipments by capacity | 5 | **87.5** |
| T2 | • Very competitive among equipment manufacturers | 5 | **87.5** |
| T3 | • Widely accepted | 10 | **87.5** |
| T4 | • A couple of functionality for each equipment | 10 | **37.5** |
| T5 | • Low flexibility<br>• More important in equipment selection | 11 | **16.5** |
| B1 | • Relatively simple but sophisticated | 6 | **16.5** |
| B2 | • Mostly old | 10 | **25** |
| B3 | • Better positioning from GPS<br>• Real-time and high quality grading from laser technology | 10 | **90** |
| I1 | • Equipment standing alone in most case | 34 | **12.5** |
| | Supply Index | **4.0** | |

**Table 6-16: Technology Supply Assessment (WF5.03)**

| **WF5.03: Construct rebar cages** | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Several but limited equipment suppliers for bending and shearing<br>• Diverse equipment by rebar size for bending<br>• A couple of tying machines, yet few prevailing tools for tying and placing | 5 | **37.5** |
| T2 | • Competitive by limited suppliers for bending and shearing tools | 5 | **37.5** |
| T3 | • Mostly proven and accepted by job site | 10 | **62.5** |
| T4 | • Limited to mostly individual or two sub tasks | 10 | **12.5** |
| T5 | • Flexible for diverse shapes<br>• Limited to rebar size and capacity | 11 | **16.5** |
| B1 | • Relatively simple but sophisticated | 6 | **16.5** |
| B2 | • Mostly old and some in research stage | 10 | **25** |
| B3 | • Not so many emerging technology for the sub-tasks | 10 | **10** |
| I1 | • Integration with rebar detailing and suppliers<br>• Pre-fabricated process by factory<br>• Little integration among sub-tasks | 34 | **37.5** |
| | Supply Index | **3.0** | |

**Table 6-17: Technology Supply Assessment (WF5.08)**

| WF5.08: Hang and manipulate sheetrock | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Limited types of tools<br>• Proprietary robotics for interior wall manipulation (Japan) | 5 | **12.5** |
| T2 | • Competitive but limited suppliers | 5 | **37.5** |
| T3 | • Widely accepted | 10 | **87.5** |
| T4 | • Very limited | 10 | **12.5** |
| T5 | • One functionality for each tool | 11 | **16.5** |
| B1 | • Simple | 6 | **16.5** |
| B2 | • Mostly old and primitive | 10 | **25** |
| B3 | • More modulization | 10 | **50** |
| I1 | • Does not exist in most prevailing tools | 34 | **12.5** |
| | Supply Index | **2.7** | |

**Table 6-18: Technology Supply Assessment (WF5.11)**

| WF5.11: Apply painting and coating | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Somewhat diverse types of equipments<br>• Several proprietary robotics | 5 | **37.5** |
| T2 | • Competitive suppliers | 5 | **62.5** |
| T3 | • Mostly proven and widely accepted on job sites and factory | 10 | **87.5** |
| T4 | • Limited | 10 | **37.5** |
| T5 | • Not much flexibility after set up | 11 | **16.5** |
| B1 | • Mix of simple and complex | 6 | **50** |
| B2 | • Mostly new and proven | 10 | **75** |
| B3 | • Beneficial for quality and safety<br>• Tele-operating machine or robotics | 10 | **70** |
| I1 | • No interface and stand alone | 34 | **12.5** |
| | Supply Index | **4.1** | |

**Table 6-19: Technology Supply Assessment (WF6.03)**

| WF6.03: Use as-built information in personnel training | | | |
|---|---|---|---|
| | Assessment | Wt. | Score |
| T1 | • Very limited prevailing tools available other than manual or multi-media materials | 5 | **12.5** |
| T2 | • Not so much competitiveness | 5 | **12.5** |
| T3 | • Mostly in development stage | 10 | **12.5** |
| T4 | • Very limited | 10 | **12.5** |
| T5 | • Specifically designed for each project or facility type | 11 | **50** |
| B1 | • Mostly simple<br>• Attempt to using advanced technology | 6 | **50** |
| B2 | • Trying to apply new, cutting-edge technologies | 10 | **75** |
| B3 | • High quality and short learning curve in training<br>• Required technologies exist mostly | 10 | **50** |
| I1 | • Mostly none<br>• Attempt to build interface with electronic as-built drawings | 34 | **37.5** |
| | Supply Index | **3.7** | |

**Table 6-20: Technology Supply Assessments and Index of WFs for the Proof Model**

| WF ID | Technology Tools | | | | | Base Technologies | | | Interface Standards | Supply Index |
|---|---|---|---|---|---|---|---|---|---|---|
| | T1 | T2 | T3 | T4 | T5 | B1 | B2 | B3 | I1 | **S**$_i$ |
| **Weight** | 5 | 5 | 10 | 10 | 11 | 6 | 10 | 10 | 34 | |
| WF1.05 | 37.5 | 37.5 | 37.5 | 37.5 | 50 | 16.5 | 25 | 50 | 37.5 | 3.7 |
| WF2.02 | 12.5 | 37.5 | 12.5 | 12.5 | 16.5 | 25 | 25 | 70 | 12.5 | 2.2 |
| WF2.05 | 87.5 | 62.5 | 87.5 | 62.5 | 50 | 75 | 75 | 70 | 62.5 | 6.8 |
| WF2.07 | 62.5 | 62.5 | 62.5 | 50 | 50 | 82.5 | 75 | 70 | 62.5 | 6.3 |
| WF3.01 | 37.5 | 37.5 | 62.5 | 12.5 | 16.5 | 16.5 | 75 | 50 | 37.5 | 3.9 |
| WF4.04 | 37.5 | 62.5 | 62.5 | 62.5 | 50 | 50 | 75 | 70 | 37.5 | 5.3 |
| WF4.06 | 37.5 | 37.5 | 37.5 | 37.5 | 50 | 50 | 75 | 90 | 62.5 | 5.7 |
| WF5.02 | 87.5 | 87.5 | 87.5 | 37.5 | 16.5 | 16.5 | 25 | 90 | 12.5 | 4.0 |
| WF5.03 | 37.5 | 37.5 | 62.5 | 12.5 | 16.5 | 16.5 | 25 | 10 | 37.5 | 3.0 |
| WF5.08 | 12.5 | 37.5 | 87.5 | 12.5 | 16.5 | 16.5 | 25 | 50 | 12.5 | 2.7 |
| WF5.11 | 37.5 | 62.5 | 87.5 | 37.5 | 16.5 | 50 | 75 | 70 | 12.5 | 4.1 |
| WF6.03 | 12.5 | 12.5 | 12.5 | 12.5 | 50 | 50 | 75 | 50 | 37.5 | 3.7 |

The Technology Supply Model assessed the WF of "Generate floor plans" the highest among the 12 WFs, while getting input from suppliers and builder about construction method and sequence suffers from the lowest level of technology supply.

## 6.6 Proof of Research Hypothesis

Proving the research hypothesis that "the relative demand for technology at the WF level is largely a function of WFCs," requires a statistical correlation test between the hypothesized technology use and the surveyed technology use with the selected 12 WFs. According to Assumption #1, the hypothesized technology use is determined by the minimum value from the WFCs-based demand assessment and the supply assessment as computed with the Technology Supply Model.

### 6.6.1 Data Summary for Research Proof

Table 6-21 lists indices for all 12 WFs: the WFC-based Technology Demand Indices (from Table 6-5), the Technology Supply Indices (from Table 6-20), the hypothesized technology use indices, and the surveyed technology use indices.

Ten out of 12 WFs determine the level of technology usage by the Technology Demand Index. This demand domination can be explained by overall low assessments of the Technology Demand Model.

Table 6-21 also lists deviations of the hypothesized usage from the actual industry usage. Four (WF2.05, WF2.07, WF4.04, and WF5.02) out of the five largest deviation show that the Supply Index is very close to the surveyed usage level;

however, low assessments of technology demand cause a large deviation from the actual level of technology usage. The WFs indicating less than 1.0 deviation (WF2.02, WF4.06, WF5.03, WF5.11, and WF6.03) can be used to interpret which factor decides the technology usage level. WF2.02 clearly shows that the low supply level determines the technology usage level. This implies that the current technology supply of WF2.02 does not meet the technology demand.

WFCs-based determination of technology demand via an index is only an approximate indicator as a result of some involvements of low applicability of WFCs and other missing factors affecting technology demand such as project characteristics or economical impact from actual development. Likewise, the technology supply model and its index computation is only an approximate indicator as a result of the limited literature survey and lack of evaluation by end-users.

**Table 6-21: Proof Model: Hypothesized Technology Use vs. Surveyed Technology Use**

| WF | WFC-based Demand | Supply | Hypothesized technology use (A) | Surveyed technology use (B) | Δ (A-B) |
|---|---|---|---|---|---|
| WF1.05 | 3.9 | 3.7 | **3.7** | **5.62** | -1.9 |
| WF2.02 | 3.9 | 2.2 | **2.2** | **2.17** | 0.0 |
| WF2.05 | 4.1 | 6.8 | **4.1** | **6.70** | -2.6 |
| WF2.07 | 4.5 | 6.3 | **4.5** | **6.39** | -1.9 |
| WF3.01 | 3.5 | 3.9 | **3.5** | **2.33** | 1.2 |
| WF4.04 | 3.7 | 5.3 | **3.7** | **5.29** | -1.6 |
| WF4.06 | 3.4 | 5.7 | **3.4** | **2.62** | 0.8 |
| WF5.02 | 2.7 | 4.0 | **2.7** | **4.94** | -2.2 |
| WF5.03 | 1.8 | 3.0 | **1.8** | **1.43** | 0.4 |
| WF5.08 | 2.5 | 2.7 | **2.5** | **1.45** | 1.0 |
| WF5.11 | 2.4 | 4.1 | **2.4** | **2.28** | 0.1 |
| WF6.03 | 2.8 | 3.7 | **2.8** | **2.99** | -0.2 |

### 6.6.2 Correlation Coefficient

The correlation coefficient, *r*, between the hypothesized technology use and the surveyed technology use is 0.813. This *r* value measures the strength of the linear relationship between two variables. In order to statistically test whether there is a significant linear relationship, the *p-value* is calculated using the statistic analysis software package, SPSS, with the critical value for $\alpha = 0.05$ and $n = 12$. SPSS testing determined that the *p-value* in this case is 0.001 and is less than $\alpha = 0.05$. Therefore, there *is* sufficient statistical evidence to support the claim of a linear correlation between the hypothesized technology use and the surveyed technology use.

Once the linear relationship is proven, the $r^2$ value, 0.661, explains the extent to which variation in the dependent variable can be explained by the independent variable. In this research the value of $r^2$ can be interpreted as "sharing between two variables." Statistically, therefore, there is 66.1% sharing between the surveyed technology use and the hypothesized technology use. Figure 6-22 displays the correlation scatter plot between the surveyed technology use and the hypothesized technology use. Because those two variables share the same meaning, the data points should be ideally plotted along with $y = x$ line. However, the hypothesized technology usages range only half of the surveyed technology usage, the trend line is steeper than $y = x$ line.

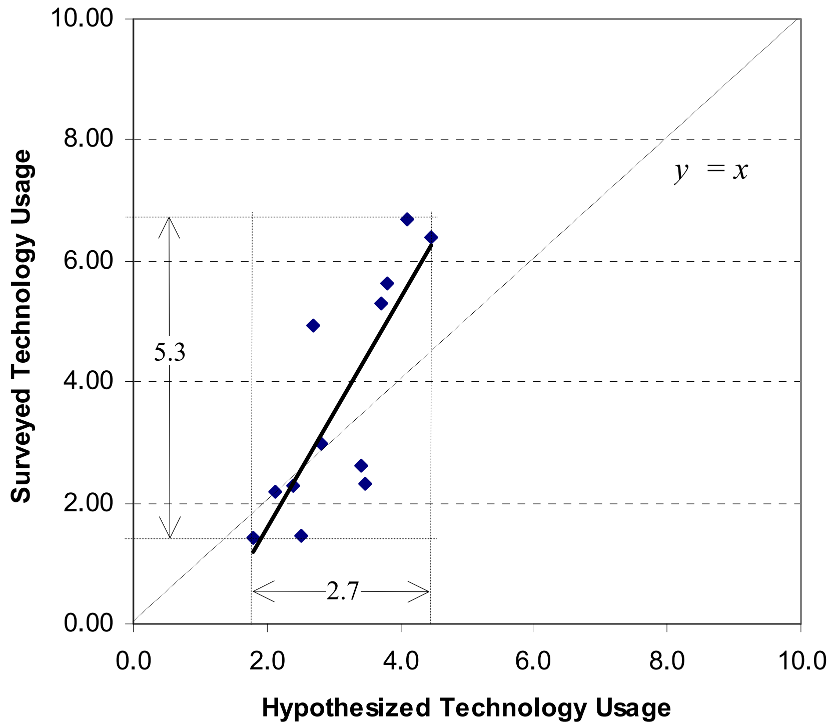



**Figure 6-22: Correlation Scatter Graph**

The smaller range of the hypothesized usage than that of the surveyed usage can be explained by the involvement of low demand potential WFCs. Elimination of several low demand potential WFCs can serve to expand the range of hypothesized technology usage. Figure 6-23 displays an expanded hypothesized technology usage range by 0.4 after eliminating three lowest demand potential WFCs (T4, P2, and M1).

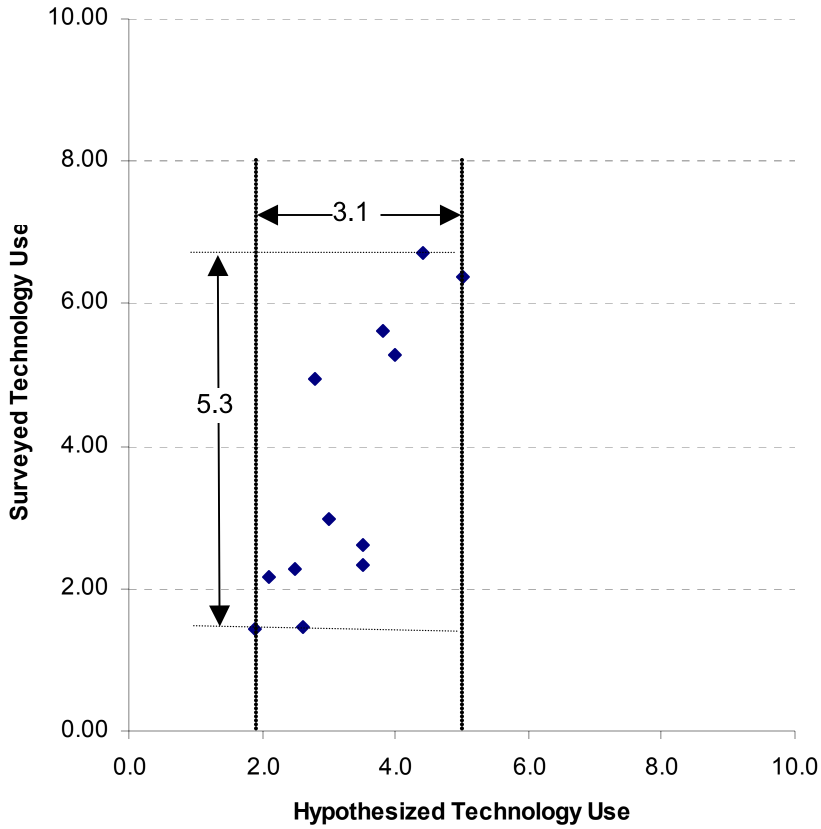



**Figure 6-23: Correlation Scatter Graph without Three Lowest Demand Potential WFCs**

### 6.6.3 Justification of Research Proof Model

While the surveyed technology use index is a relatively precise measure, the estimated technology use measure relies on some subjective assessments and prone to error to some degrees. Each estimate involves a component of measurement error and random error. It is possible that the observed correlation is due to a coincidental correlation of those errors and the surveyed technology use. With a larger number *n*, the number of WFs for the Research Proof Model, any potential effects of random error would be reduced; however, the small sample size (*n* = 12) makes it difficult to rule out this possibility. Nevertheless, on the basis of the data that the author was able to collect, the high correlation suggests a strong relationship between the two variables.

Two data sets for the correlation test involve a strong linearity in their scale. The surveyed technology usages are based a total of 209 datasets. Figure 4-2 displays a linear distribution between the range of 1.43 and 6.67. The linearity of the hypothesized technology usage can be found from the robustness of the Supply Model in Figure 6-18. Nine assessment factors with three to five scales on 0 to 10 scale are large enough to generate a linear index system.

# CHAPTER 7 RESEARCH APPLICATION

## 7.1 Application Model Development

Once the Research Proof Model is validated, with technology usage data from the industry survey WFCs can be used to evaluate technology demand of a specific WF. According to Assumption #2, the level of technology use i.e., the mean value of IA Metrics, with WFCs based-demand can be used to deduce technology supply. By comparing the levels between supply and demand according to Assumption #3, gap size, which is defined as technology demand minus technology supply, can be determined (Equation 2). This gap size directly refers to R&D prioritization according to Assumption #4.

$$\textit{Gap Index} = \textit{Technology Demand Index} - \textit{Technology Supply Index} \qquad \textit{Equation (2)}$$

The advantage of the Application Model is that it can produce R&D prioritization without the supply model, which is a time-consuming process requiring considerable efforts. Figure 7-1 depicts the procedures and the applied assumptions in the Application Model.

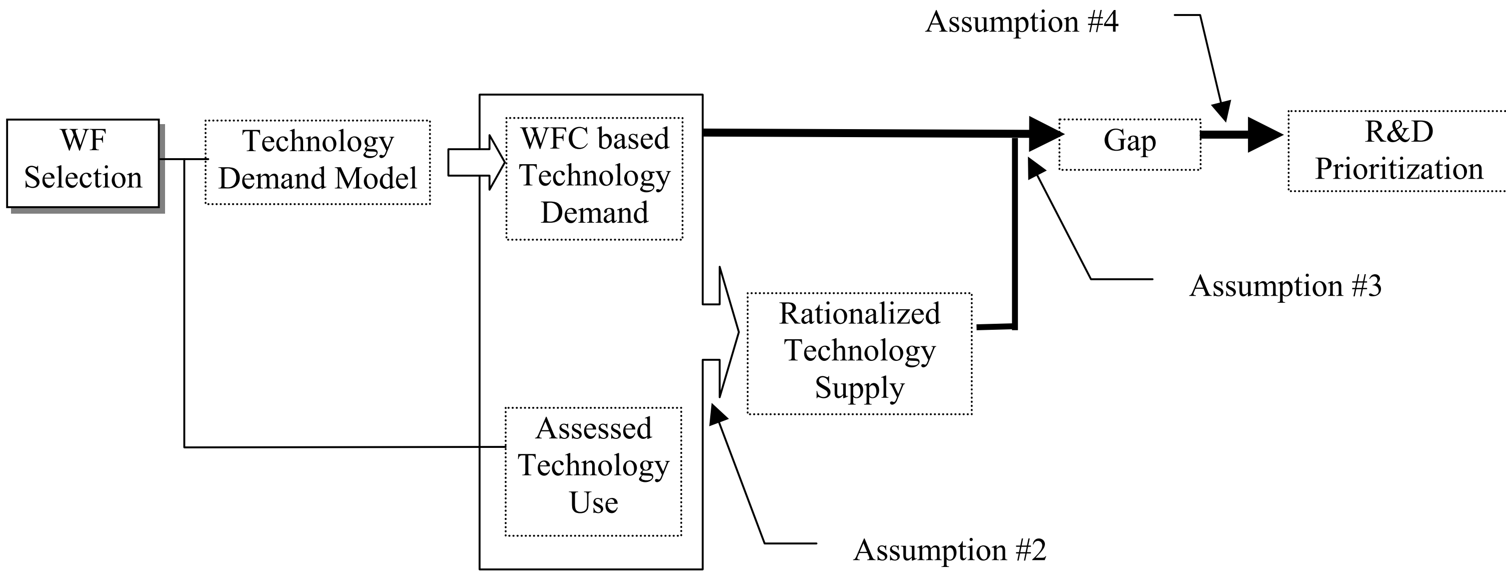



**Figure 7-1: Research Application Model**

## 7.2 Data Collection for the Application Model

In prioritizing R&D, the most interesting and beneficial application is to identify where a significant gap exists. The largest gap exists where technology demand is high, but supply is low. The combination of high demand and low supply leads to low technology use (Assumption #1). Therefore, the Application Model would be more meaningful with low technology use WFs than with medium or high use WFs.

Data collection for the Application model starts with WF selection and survey participants selection. Several criteria for WF selection for the Application Model were established:

- Apply for a total of 10 WFs.
- WFs with Low technology usage.
- No overlap with the WFs in the Proof Model.
- At least one WF from each project phase.

Table 7-1 lists the WFs selected for the Application Model based on the above criteria. Eight out of 10 WFs are low technology use WFs. Two medium technology use WFs, WF1.01 and WF6.08 were also included, as they are the lowest technology use WFs available in Phase 1 and 6.

Three CEPM (Construction Engineering and Project Management) faculty members from the Department of Civil Engineering at the University of Texas at

Austin participated in the survey on the characterization of the selected 10 WFs (Appendix D).

**Table 7-1: Work Functions for the Application Model**

| ID | Work Functions for the Application Model | Technology Usage | |
|---|---|---|---|
| | | Mean | S.D. |
| 4.07 | Link field material managers to suppliers | 1.52 | 2.71 |
| 3.12 | Plan the transportation routes of large items from the fabricator to the job site | 1.97 | 3.02 |
| 4.11 | Communicate design changes to field personnel | 1.96 | 3.07 |
| 3.11 | Monitor the progress of fabricators | 1.97 | 3.02 |
| 4.03 | Maintain daily job diary | 2.18 | 3.25 |
| 4.09 | Communicate Request for Information & responses | 2.62 | 3.36 |
| 1.01 | Conduct market analysis or need analysis for a new facility | 4.30 | 3.36 |
| 2.13 | Check the design against owner requirements (e.g. design reviews) and code requirements | 3.23 | 3.87 |
| 5.14 | Weld pipes | 2.43 | 3.08 |
| 6.08 | Update as-built drawings | 3.99 | 3.29 |

## 7.3 Data Collection Results

### 7.3.1 Characterization of Work Function

Table 7-2 summarizes the survey results in the same way in the Research Proof Model. Again, the shaded boxes represent a high applicability between a WF and WFCs. All the scores are based on 0 to 10 scale in order to keep consistency with other indices. Nine WFs have a strong association with WFC I4, involvement of many different formats of data, and D2, being error prone. WF4.03 shows significantly different characteristics from other WFs from Phase 4.

**Table 7-2: Characterization of Selected Work Functions – Research Application Model**

| WFC ID | 1.01 | 2.13 | 3.11 | 3.12 | 4.03 | 4.07 | 4.09 | 4.11 | 5.14 | 6.07 |
|---|---|---|---|---|---|---|---|---|---|---|
| I1 | 10.00 | | 1.67 | 5.56 | | | | | | |
| D1 | 8.89 | 7.78 | 5.56 | 5.56 | 8.33 | 7.78 | 10.00 | 8.89 | | |
| I2 | 10.00 | 4.44 | 5.56 | 5.56 | | | | | | |
| H1 | 2.50 | | 6.67 | 5.00 | | | | | | 5.00 |
| I3 | 2.22 | 7.78 | | | | | | | | |
| M1 | 6.67 | 6.67 | | | | | | | | |
| I4 | 6.67 | 7.78 | 6.67 | 8.33 | 8.89 | 7.78 | 10.00 | 10.00 | | 7.78 |
| D2 | 7.78 | 8.89 | 6.67 | 6.67 | 8.89 | 8.89 | 8.89 | 10.00 | | 7.78 |
| I5 | | 7.78 | 6.67 | 7.78 | 5.56 | 10.00 | 8.89 | 8.89 | | 8.89 |
| M2 | | 8.33 | 7.78 | 8.89 | 3.33 | 10.00 | 10.00 | 6.67 | | |
| M3-Cost | | 3.33 | | | 5.00 | | | 1.12 | | |
| M3-Schedule | | | 10.00 | 10.00 | | 3.33 | 6.67 | 5.55 | | |
| M3-Quality | | 6.67 | | | 5.00 | 6.67 | 3.33 | 3.33 | | |
| M3-Safety | | | | | | | | | | |
| M4 | | 7.78 | 8.89 | 7.78 | 6.67 | 10.00 | 10.00 | 10.00 | | |
| I6 | | | 5.56 | 5.56 | 4.44 | 6.67 | 4.44 | 4.44 | | |
| D3 | | | 3.33 | 7.78 | 3.33 | 3.33 | 1.11 | 0.00 | | |
| T1 | | | 4.44 | 5.56 | 1.67 | 2.22 | 8.89 | 8.89 | | |
| P1 | | | 7.78 | 7.78 | 0.00 | 5.56 | 10.00 | 10.00 | | |

**Table7-2 (continued)**

| WFC ID | 1.01 | 2.13 | 3.11 | 3.12 | 4.03 | 4.07 | 4.09 | 4.11 | 5.14 | 6.07 |
|---|---|---|---|---|---|---|---|---|---|---|
| I7 | | | 8.33 | 3.33 | 8.89 | 8.89 | 10.00 | 8.89 | | |
| D4 | | | | | | | | | 8.89 | 7.78 |
| H2 | | | | | | | | | 2.22 | 4.44 |
| P2 | | | | | | | | | 8.89 | 2.22 |
| P3 | | | | | | | | | 8.89 | 4.44 |
| T2 | | 8.89 | | | 3.33 | 5.00 | 2.22 | 7.78 | 8.89 | |
| T3-Cost | | | | | | | | | 5.00 | |
| T3-Schedule | | | 10.00 | 10.00 | | | | | | |
| T3-Quality | | | | | | | | | 5.00 | |
| T3-Safety | | | | | | | | | | |
| T4 | | 2.22 | | | 4.44 | 4.44 | 3.33 | 5.56 | 6.67 | |
| M5 | | 6.67 | | | 3.33 | 7.78 | 8.89 | 8.89 | 5.00 | |
| D5 | | | | | | | | | 8.33 | 1.67 |
| D6 | | | | | | | | | 5.56 | 3.33 |
| H3 | | | | | | | | | 10.00 | 6.67 |
| T5 | | | | | | | | | 8.89 | 0.00 |
| T6 | | | | | | | | | 8.33 | 3.33 |
| D7 | | | | | | | | | 8.89 | 8.89 |

### 7.3.2 Application for the Prioritization of Technology R&D

The Technology Demand Index is calculated by the same equation used in the Research Proof Model. No WF indicates "high" demand in an absolute scale. WF4.09, "Communicate request for information & responses," shows the highest demand among the 10 WFs. With the knowledge of the technology demand and use, Assumption #2 is used to deduce the technology supply. Nine out of 10 WFs indicate a lower level of technology use than technology demand, which means that the technology use is determined by the supply level. Only WF6.07 generates an "Impossible" situation. This small number of conflict situations is possible because the WFs were intentionally selected in a low usage level. Table 7-3 lists all the data sets required for the Application Model. The gap between technology supply and demand is simply calculated from Equation 2, and prioritization of R&D is ranked by the gap size.

Results from the Application Model indicate that WF4.07, "Link field material manager to suppliers," deserves the highest priority for future R&D among the ten WFs applied. WF4.11, WF3.12, WF3.11, and WF4.09 also are associated with a relatively large gap; therefore, they deserve a higher priority than other WFs. The number of WFs analyzed is too small to generalize any trend associated with project phases. In order to generalize R&D prioritization associated with project phases and build a R&D roadmap for project technology development, further data collection with the remaining WFs is needed. Figure 7-2 graphically displays the gap assessed by the Application Model. The graph shows that relatively high levels of technology supply in WF1.01 and WF2.13, which results in small gaps between the demand and supply. WF4.03 indicates a low level of technology demand, which causes a small gap between the demand and supply, although the supply level is low.

**Table 7-3: Results of Application Model**

| WF ID | Work Function | WFC-based tech. demand | Surveyed tech. use | Deduced tech. supply | Gap between demand and supply | Priority ranking |
|---|---|---|---|---|---|---|
| WF1.01 | Conduct market analysis or need analysis for a new facility | 5.0 | 4.30 | 4.3 | 0.7 | **9** |
| WF2.13 | Check the design against owner requirements (e.g. design reviews) and code requirements | 4.7 | 3.23 | 3.2 | 1.5 | **7** |
| WF3.11 | Monitor the progress of fabricators | 4.8 | 1.97 | 2.0 | 2.8 | **4** |
| WF3.12 | Plan the transportation routes of large items from the fabricator to the job site | 4.9 | 1.97 | 2.0 | 2.9 | **2** |
| WF4.03 | Maintain daily job diary | 3.6 | 2.18 | 2.2 | 1.4 | **8** |
| WF4.07 | Link field material managers to suppliers | 4.7 | 1.52 | 1.5 | 3.2 | **1** |
| WF4.09 | Communicate Request for Information & responses | 5.1 | 2.62 | 2.6 | 2.5 | **5** |
| WF4.11 | Communicate design changes to field personnel | 4.9 | 1.96 | 2.0 | 2.9 | **2** |
| WF5.14 | Weld pipes | 4.2 | 2.43 | 2.4 | 1.8 | **6** |
| WF6.07 | Update as-built drawings | 3.3 | 3.99 | Imp | N/A | N/A |

Imp: Impossible
N/A: Not Applicable

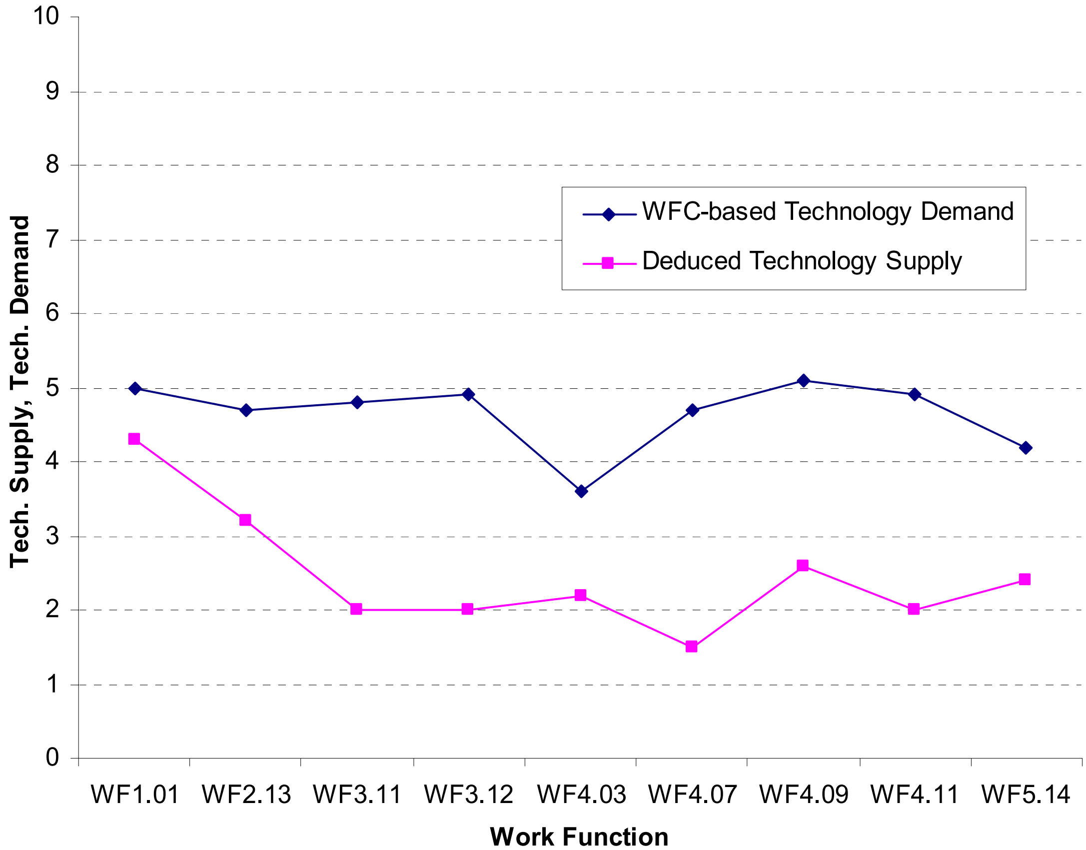



**Figure 7-2: Comparison of Measures of Technology Demand and Technology Supply**

# CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

## 8.1 Review of Research Objectives

The goal of this study has been to develop a theoretical model that proves the value of WFCs as technology demand driver factors and to apply them in prioritizing needs for technology R&D for capital facility projects. Two primary research objectives and sub-objectives are listed as follows:

1. Propose and test a proof model for using work function characteristics to gain insight into the technology demand of an individual work function.
    - Understand the degrees of technology use at the WF level.
    - Develop a comprehensive list of WFCs that are applied to WFs in capital facility projects.
    - Develop a model to assess technology demand based on WFCs.
    - Develop a model to assess technology supply in general.
2. Develop an application framework for effectively prioritizing industry R&D pursuits associated with work function level technologies by means of work function characteristics-based technology demand assessment.

## 8.2 Conclusions

***Technology Usage at WF Level***

From statistical analysis of the technology use at the WF level, the mean values of technology use for individual WFs range from 1.43 to 6.70. CAD technology related WFs in the Design Phase involves relatively high levels of use, while low technology use WFs pertain to Phase 3, 4, and 5. Communications among participants that require more than simple data transfer are generally associated with low levels of technology usage.

From the ANOVA test combined with data class variables, the Construction Management Phase generated the greatest number of significant differences. This result could imply that levels of technology use during the Construction Management Phase had wider variances than other phases depending on project characteristics. Another distinguishing factor affecting levels of technology use is project size. Medium size projects, ranging between $5 million and $50 million of Total Installed Cost, indicate higher levels of technology use than Large or Small projects. Statistical analyses of technology usage at the WF level and according to data class variables provided better understanding of the variation of technology usage by project characteristics.

### ***Work Function Characteristics as Technology Demand Drivers***

A total of 31 work function characteristics were developed for common WFs in capital facility projects. The data collection of the linkage between WFCs and technology demand indicated that the WFCs associated with either Data and Information aspects or repetitive or iterative procedures drive technology demand the most. Six out of seven WFCs that pertain to Data and Information are associated with the *high* level in an absolute scale. This suggests that a well-structured database system and technologies that replace repetitive human action should be very beneficial. The five most technology demanding WFCs identified in this study are listed below.

- Historical data from previous projects are required for execution.
- WF involves significant amount of data updating.
- WF involves iterations and revisions.
- WF involves repetitive activity.
- Data accuracy is crucial to successful WF performance.

The five least technology demanding WFCs identified in this study are listed below.

- WF management operates in close proximity to workers.
- A specialty organization is involved in most cases.
- WF product is physically large and bulky.
- WF involves relatively high uncertainty in safety performance.
- WF relies on or requires physical output products of many previous WFs.

***Research Proof Model***

The Research Proof Model was used to statistically prove a significant correlation between the hypothesis-based technology use and the surveyed technology use. The statistical proof justified the two sub-models, the Technology Demand Model and the Technology Supply Model. The justification of the Technology Demand Model validated the research hypothesis that the relative demand for technology at the WF level is largely a function of WFCs. However, both the Technology Demand and Technology Supply Models are only approximate indicators.

***Application Model***

Finally, among 10 selected WFs, the Application Model was used to determine high-priority needs for R&D. The following five WFs were identified:

- Link field material managers to suppliers.
- Communicate design changes to field personnel.
- Plan the transportation routes of large items from the fabricator to the job site.
- Monitor the progress of fabricators.
- Communicate Request for Information & responses.

However, WFC-based priority appears more applicable to IT than physical automation technologies. The Application Model is intended to complement conventional methods of prioritization of technology R&D, rather than to replace them. The two approaches should be contemplated in parallel in order to provide future R&D roadmap and its justification for capital projects.

## 8.3 Recommendations

This study has successfully initiated the use of work function characteristics as a research “building block.” The following recommendations should be considered for future related studies.

- The technology usage surveyed should be updated in the next five years to more accurately reflect new trends in web-based technology
- A complete survey of all 68 WFs can provide an industry-wide roadmap for future technology R&D in capital facility projects.
- Some WFs may be associated with different characteristics depending on project characteristics such as industry sector involved or project size. Analysis of WFC related to data class variables may offer deeper insights into demand for technology.
- Specific identification of potential benefits associated with individual WFCs may provide better understanding of WFCs as project performance drivers.
- The gap defined in this study may be a good estimator associated with potential benefits of R&D, but may not adequately account for the relative

cost of actual development. A subsequent research should give greater consideration to this issue.

# APPENDIX A

## ASSESSMENT OF THE LINKAGE BETWEEN WORK FUNCTION CHARACTERISTICS AND TECHNOLOGY DEMAND

**Respondent Information**

| | | |
|---|---|---|
| Name: | | |
| Company name: | Title: | |
| Department: | Years in industry or academia: | |
| Phone Number:<br>**(    )    -** | Fax Number:<br>**(    )  -** | E-mail Address: |

**Organization information**

Your Organization Type

| | |
|---|---|
| □ Public Owner | □ Design-Build or EPC |
| □ Private Owner | □ Subcontractor or Specialty contractor |
| □ Design Consultant or A/E | □ University or Research Institute |
| □ Prime Contractor or GC | Other (please describe): ____________________________ |

Primary industry sector involvement: □ Building □ Infrastructure □ Industrial

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ECJ 5.2
University of Texas
Austin, TX 78712

**Assessment of work function characteristics to technology demand**

| | |
|---|---|
| Direction: | To what extent do you agree that the listed work function characteristic (WFC) suggests that benefits would result from *added technology*?<br><br>Please respond by circling one of five optional responses:<br>**SA** = Strongly Agree, **A** = Agree, **N** = Neutral, **D** = Disagree, **DK** = Don't Know |
| Caution: | Work Function Characteristics are not limited to a specific work function. |

### Example of assessment:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 18 | WF involves repetitive activity. | SA | A | N | D | DK | |
| | *Work functions that involve repetitive activity could generally benefit from added technology because automation benefits can be leveraged with repetition.* | | | | | | |

| ID | Generic Work Function Characteristic | **WFC suggests that benefits would result from added technology.** | | | | | Example application (Optional) |
|---|---|---|---|---|---|---|---|
| 1 | WF involves a lot of uncertainty or probabilistic information. | SA | A | N | D | DK | |
| 2 | WF involves iterations and revisions. | SA | A | N | D | DK | |
| 3 | Historical data from previous projects are required for execution. | SA | A | N | D | DK | |
| 4 | Many individuals are involved to perform WF. | SA | A | N | D | DK | |
| 5 | WF relies on industry technical standards. | SA | A | N | D | DK | |
| 6 | A specialty organization is involved in most cases. | SA | A | N | D | DK | |
| 7 | WF data are in many different formats. | SA | A | N | D | DK | |
| 8 | WF is error prone. | SA | A | N | D | DK | |
| 9 | Data accuracy is crucial to successful WF performance. | SA | A | N | D | DK | |
| 10 | Several different organizations are involved in WF. | SA | A | N | D | DK | |
| 11 | Responsible individual for WF must communicate frequently with others. | SA | A | N | D | DK | |

**Assessment of work function characteristics to technology demand**

| ID | Work Function Characteristics | **WFC suggests that benefits would result from added technology.** | | | | | Example application (Optional) |
|---|---|---|---|---|---|---|---|
| 12-1 | *Cost* is the primary performance driver to WF. | SA | A | N | D | DK | |
| 12-2 | *Schedule* is the primary performance driver to WF. | SA | A | N | D | DK | |
| 12-3 | *Quality* is the primary performance driver to WF. | SA | A | N | D | DK | |
| 12-4 | *Safety* is the primary performance driver to WF. | SA | A | N | D | DK | |
| 13 | Security of related data is very important. | SA | A | N | D | DK | |
| 14 | WF procedures are driven by regulations. | SA | A | N | D | DK | |
| 15 | WF is a critical path activity in most cases. | SA | A | N | D | DK | |
| 16 | Performance of many subsequent WFs relies heavily on this WF. | SA | A | N | D | DK | |
| 17 | WF involves significant amount of data updating. | SA | A | N | D | DK | |
| 18 | WF involves repetitive activity. | SA | A | N | D | DK | |
| 19 | WF involves many individuals with different skills and specialties. | SA | A | N | D | DK | |
| 20 | WF product is physically large and bulky. | SA | A | N | D | DK | |
| 21 | Errors are difficult to fix or require a large amount of resources to fix. | SA | A | N | D | DK | |
| 22 | WF activity requires spatial coordination. | SA | A | N | D | DK | |

## Assessment of work function characteristics to technology demand

| WFC ID | Work Function Characteristics | **WFC suggests that benefits would result from added technology.** | | | | | Example application (Optional) |
|---|---|---|---|---|---|---|---|
| 23-1 | WF involves relatively high uncertainty in *cost* performance. | SA | A | N | D | DK | |
| 23-2 | WF involves relatively high uncertainty in *schedule* performance. | SA | A | N | D | DK | |
| 23-3 | WF involves relatively high uncertainty in *quality* performance. | SA | A | N | D | DK | |
| 23-4 | WF involves relatively high uncertainty in *safety* performance. | SA | A | N | D | DK | |
| 24 | WF management operates in close proximity to workers. | SA | A | N | D | DK | |
| 25 | WF involves high probability of change. | SA | A | N | D | DK | |
| 26 | Some WF resources are often idle. | SA | A | N | D | DK | |
| 27 | WF procedures are very complex. | SA | A | N | D | DK | |
| 28 | User’s, worker's, or operator's experience is critical to performance. | SA | A | N | D | DK | |
| 29 | WF involves environmental hazard. | SA | A | N | D | DK | |
| 30 | WF is costly to execute. | SA | A | N | D | DK | |
| 31 | WF relies on or requires physical output products of many previous WF. | SA | A | N | D | DK | |

# APPENDIX B-1

## CHARACTERIZING WORK FUNCTIONS

## - FOR OWNER-RESPONSIBLE WORK FUNCTIONS

**Respondent Information**

| | | |
|---|---|---|
| Name: | | |
| Company name: | Title: | |
| Department: | Years in the construction industry: | |
| Phone Number:<br>( ) - | Fax Number:<br>( ) - | E-mail Address: |

**Organization information**

| |
|---|
| Primary industry sector involvement: □ Building □ Infrastructure □ Industrial |

**Please return to:** James T. O'Connor ,**or fax to:** 512-471-3191
Department of Civil Engineering
ECJ 5.2
University of Texas
Austin, TX 78712

| | |
|---|---|
| Direction: | To what extent do you agree that the listed work function characteristic applies to the work function at the top of each assessment?<br><br>Please respond by circling one of the provided optional responses.<br>Abbreviation are as follows:<br>**SA** = Strongly Agree, **A** = Agree, **N** = Neutral, **D** = Disagree, **DK** = Don't Know |

Work Function (WF): **Develop a milestone schedule from the scope of work**
(Front End Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves uncertainty or probabilistic information. | SA | A | N | D | DK |
| 2 | This WF involves iterations and revisions. | SA | A | N | D | DK |
| 3 | Historical data from previous projects are required for executing this WF | SA | A | N | D | DK |
| 4 | How many individuals are involved in performing this WF? | 1-2 | 3-5 | 6 or more | | DK |
| 5 | This WF relies on industry technical standards. | SA | A | N | D | DK |
| 6 | A specialty organization is involved in performing this WF. | SA | A | N | D | DK |
| 7 | The data involved in this WF are in many different formats. | SA | A | N | D | DK |
| 8 | This WF is error prone. | SA | A | N | D | DK |

Work Function (WF): **Determine the lead times required to order equipment and materials** (Procurement Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves uncertainty or probabilistic information. | SA | A | N | D | DK |
| 2 | This WF involves iterations and revisions. | SA | A | N | D | DK |
| 3 | Historical data from previous projects are required for executing this WF | SA | A | N | D | DK |
| 4 | How many individuals are involved in performing this WF? | 1 | 2-5 | 6 or more | | DK |
| 5 | The data involved in this WF are in many different formats. | SA | A | N | D | DK |
| 6 | This WF is error prone. | SA | A | N | D | DK |
| 7 | Data accuracy is crucial to successful performance of this WF. | SA | A | N | D | DK |
| 8 | How many different organizations are involved in performing this WF? | 0 | 1 | 2 | 3 or more | DK |
| 9 | Primary performance driver of WF is which of the following. | Quality | Cost | Schedule | Safety | |
| 10 | Responsible individual must communicate frequently with others. | SA | A | N | D | DK |
| 11 | Security of related data is very important. | SA | A | N | D | DK |
| 12 | The procedures of this WF are driven by regulations. | SA | A | N | D | DK |
| 13 | This WF is a critical path activity in most cases. | SA | A | N | D | DK |
| 14 | Performance of many subsequent WFs relies heavily on this WF. | SA | A | N | D | DK |
| 15 | This WF involves a significant amount of data updating. | SA | A | N | D | DK |
| 16 | This WF involves relatively high uncertainty in the following. | Quality | Cost | Schedule | Safety | |

Work Function (WF): **Use as-built information in personnel training**
(Operation and Maintenance Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | How many individuals are involved in performing this WF? | 1-2 | 3-5 | 6 or more | | DK |
| 2 | The data involved in this WF data are in many different formats. | SA | A | N | D | DK |
| 3 | This WF is error prone. | SA | A | N | D | DK |
| 4 | Data accuracy is crucial to successful performance of this WF. | SA | A | N | D | DK |
| 5 | This WF involves repetitive activity. | SA | A | N | D | DK |
| 6 | This WF involves many individuals with different skills and specialties. | SA | A | N | D | DK |
| 7 | The products of this WF are physically large and bulky. | SA | A | N | D | DK |
| 8 | Errors from this WF are difficult to fix or require a large amount of resources to fix. | SA | A | N | D | DK |
| 9 | Some resources of this WF are often idle. | SA | A | N | D | DK |
| 10 | The procedures of this WF are very complex. | SA | A | N | D | DK |
| 11 | User's, worker's, or operator's experience is critical to performance of this WF. | SA | A | N | D | DK |
| 12 | This WF involves environment hazard. | SA | A | N | D | DK |
| 13 | This WF is costly to execute. | SA | A | N | D | DK |
| 14 | This WF relies on or requires physical output products of many previous WFs. | SA | A | N | D | DK |

# APPENDIX B-2

## CHARACTERIZING WORK FUNCTIONS

## - FOR A/E-RESPONSIBLE WORK FUNCTIONS

**Respondent Information**

| | | |
|---|---|---|
| Name: | | |
| Company name: | Title: | |
| Department: | Years in the construction industry: | |
| Phone Number:<br>( ) - | Fax Number:<br>( ) - | E-mail Address: |

**Organization information**

| |
|---|
| Primary industry sector involvement: □ Building □ Infrastructure □ Industrial |

**Please return to:** James T. O'Connor ,**or fax to:** 512-471-3191
Department of Civil Engineering
ECJ 5.2
University of Texas
Austin, TX 78712

| Direction: | To what extent do you agree that the listed work function characteristic applies to the work function at the top of each assessment?<br><br>Please respond by circling one of the provided optional responses.<br>Abbreviation are as follows:<br>**SA** = Strongly Agree, **A** = Agree, **N** = Neutral, **D** = Disagree, **DK** = Don't Know |
|---|---|

Work Function (WF): **Get input from builders and suppliers regarding construction methods selection and sequence** (Design Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | This WF involves iterations and revisions. | SA | A | N | D | DK | | |
| 2 | Historical data from previous projects are required for executing this WF | SA | A | N | D | DK | | |
| 3 | This WF relies on industry technical standards. | SA | A | N | D | DK | | |
| 4 | A specialty organization is involved in performing this WF | SA | A | N | D | DK | | |
| 5 | The data involved in this WF are in many different formats. | SA | A | N | D | DK | | |
| 6 | This WF is error prone. | SA | A | N | D | DK | | |
| 7 | Data accuracy is crucial to successful performance of this WF. | SA | A | N | D | DK | | |
| 8 | How many different organizations are involved in performing this WF? | 0 | 1 | 2 | 3 or more | DK | | |
| 9 | Primary performance driver of this WF is which of the following. | Quality | Cost | Schedule | Safety | | | |
| 10 | Responsible individual must communicate frequently with others. | SA | A | N | D | DK | | |
| 11 | This WF activity requires spatial coordination. | SA | A | N | D | DK | | |
| 12 | Management of this WF operates in close proximity to workers. | SA | A | N | D | DK | | |
| 13 | This WF involves high probability of change. | SA | A | N | D | DK | | |

| | |
|---|---|
| Direction: | To what extent do you agree that the listed work function characteristic applies to the work function at the top of each assessment?<br><br>Please respond by circling one of the provided optional responses.<br>Abbreviation are as follows:<br>**SA** = Strongly Agree, **A** = Agree, **N** = Neutral, **D** = Disagree, **DK** = Don't Know |

Work Function (WF): **<u>Design the structural systems and related drawings</u>**
(Design Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves iterations and revisions. | SA | A | N | D | DK |
| 2 | Historical data from previous projects are required for executing this WF | SA | A | N | D | DK |
| 3 | This WF relies on industry technical standards. | SA | A | N | D | DK |
| 4 | A specialty organization is involved in performing this WF | SA | A | N | D | DK |
| 5 | The data involved in this WF are in many different formats. | SA | A | N | D | DK |
| 6 | This WF is error prone. | SA | A | N | D | DK |
| 7 | Data accuracy is crucial to successful performance of this WF. | SA | A | N | D | DK |
| 8 | How many different organizations are involved in performing this WF? | 0 | 1 | 2 | 3 or more | DK |
| 9 | Primary performance driver of this WF is which of the following. | Quality | Cost | Schedule | Safety | |
| 10 | Responsible individual must communicate frequently with others. | SA | A | N | D | DK |
| 11 | This WF activity requires spatial coordination. | SA | A | N | D | DK |
| 12 | Management of this WF operates in close proximity to workers. | SA | A | N | D | DK |
| 13 | This WF involves high probability of change. | SA | A | N | D | DK |

| | |
|---|---|
| Direction: | To what extent do you agree that the listed work function characteristic applies to the work function at the top of each assessment?<br><br>Please respond by circling one of the provided optional responses.<br>Abbreviation are as follows:<br>**SA** = Strongly Agree, **A** = Agree, **N** = Neutral, **D** = Disagree, **DK** = Don't Know |

Work Function (WF): **Generate facility floor plans** (Design Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves iterations and revisions. | SA | A | N | D | DK |
| 2 | Historical data from previous projects are required for executing this WF | SA | A | N | D | DK |
| 3 | This WF relies on industry technical standards. | SA | A | N | D | DK |
| 4 | A specialty organization is involved in performing this WF | SA | A | N | D | DK |
| 5 | The data involved in this WF are in many different formats. | SA | A | N | D | DK |
| 6 | This WF is error prone. | SA | A | N | D | DK |
| 7 | Data accuracy is crucial to successful performance of this WF. | SA | A | N | D | DK |
| 8 | How many different organizations are involved in performing this WF? | 0 | 1 | 2 | 3 or more | DK |
| 9 | Primary performance driver of this WF is which of the following. | Quality | Cost | Schedule | Safety | |
| 10 | Responsible individual must communicate frequently with others. | SA | A | N | D | DK |
| 11 | This WF activity requires spatial coordination. | SA | A | N | D | DK |
| 12 | Management of this WF operates in close proximity to workers. | SA | A | N | D | DK |
| 13 | This WF involves high probability of change. | SA | A | N | D | DK |

# APPENDIX B-3

## CHARACTERIZING WORK FUNCTIONS

## - FOR GENERAL CONTRACTOR-RESPONSIBLE WORK FUNCTIONS

**Respondent Information**

| | | |
|---|---|---|
| Name: | | |
| Company name: | Title: | |
| Department: | Years in the construction industry: | |
| Phone Number:<br>(     )     - | Fax Number:<br>(     )  - | E-mail Address: |

**Organization information**

| |
|---|
| Primary industry sector involvement: □ Building □ Infrastructure □ Industrial |

**Please return to:** James T. O'Connor ,**or fax to:** 512-471-3191
Department of Civil Engineering
ECJ 5.2
University of Texas
Austin, TX 78712

| Direction: | To what extent do you agree that the listed work function characteristic applies to the work function at the top of each assessment?<br><br>Please respond by circling one of the provided optional responses.<br>Abbreviation are as follows:<br>**SA** = Strongly Agree, **A** = Agree, **N** = Neutral, **D** = Disagree, **DK** = Don't Know |
|---|---|

Work Function (WF): **<u>Determine the lead times required to order equipment and materials</u>** (Procurement Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves uncertainty or probabilistic information. | SA | A | N | D | DK |
| 2 | This WF involves iterations and revisions. | SA | A | N | D | DK |
| 3 | Historical data from previous projects are required for executing this WF | SA | A | N | D | DK |
| 4 | How many individuals are involved in performing this WF? | 1 | 2-5 | 6 or more | | DK |
| 5 | The data involved in this WF are in many different formats. | SA | A | N | D | DK |
| 6 | This WF is error prone. | SA | A | N | D | DK |
| 7 | Data accuracy is crucial to successful performance of this WF. | SA | A | N | D | DK |
| 8 | How many different organizations are involved in performing this WF? | 0 | 1 | 2 | 3 or more | DK |
| 9 | Primary performance driver of WF is which of the following. | Quality | Cost | Schedule | Safety | |
| 10 | Responsible individual must communicate frequently with others. | SA | A | N | D | DK |
| 11 | Security of related data is very important. | SA | A | N | D | DK |
| 12 | The procedures of this WF are driven by regulations. | SA | A | N | D | DK |
| 13 | This WF is a critical path activity in most cases. | SA | A | N | D | DK |
| 14 | Performance of many subsequent WFs relies heavily on this WF. | SA | A | N | D | DK |
| 15 | This WF involves a significant amount of data updating. | SA | A | N | D | DK |
| 16 | This WF involves relatively high uncertainty in the following. | Quality | Cost | Schedule | Safety | |

Work Function (WF): **Track the inventory of materials on site** (Construction Management Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves iterations and revisions. | SA | A | N | D | DK |
| 2 | The data involved in this WF are in many different formats. | SA | A | N | D | DK |
| 3 | This WF is error prone. | SA | A | N | D | DK |
| 4 | Data accuracy is crucial to successful performance of this WF. | SA | A | N | D | DK |
| 5 | How many different organizations are involved in performing this WF? | 0 | 1 | 2 | 3 or more | DK |
| 6 | Primary performance driver of WF is which of the following. | Quality | Cost | Schedule | | Safety |
| 7 | Responsible individual must communicate frequently with others. | SA | A | N | D | DK |
| 8 | Security of related data is very important. | SA | A | N | D | DK |
| 9 | The procedures of this WF are driven by regulations. | SA | A | N | D | DK |
| 10 | This WF is a critical path activity in most cases. | SA | A | N | D | DK |
| 11 | Performance of many subsequent WFs relies heavily on this WF. | SA | A | N | D | DK |
| 12 | This WF involves a significant amount of data updating. | SA | A | N | D | DK |
| 13 | This WF activity requires spatial coordination. | SA | A | N | D | DK |
| 14 | Management of this WF operates in close proximity to workers. | SA | A | N | D | DK |
| 15 | This WF involves high probability of change. | SA | A | N | D | DK |

Work Function (WF): **Update the current cost forecast** (Construction Management Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves iterations and revisions. | SA | A | N | D | DK |
| 2 | The data involved in this WF are in many different formats. | SA | A | N | D | DK |
| 3 | This WF is error prone. | SA | A | N | D | DK |
| 4 | Data accuracy is crucial to successful performance of this WF. | SA | A | N | D | DK |
| 5 | How many different organizations are involved in performing this WF? | 0 | 1 | 2 | 3 or more | DK |
| 6 | Primary performance driver of WF is which of the following. | Quality | Cost | Schedule | Safety | |
| 7 | Responsible individual must communicate frequently with others. | SA | A | N | D | DK |
| 8 | Security of related data is very important. | SA | A | N | D | DK |
| 9 | The procedures of this WF are driven by regulations. | SA | A | N | D | DK |
| 10 | This WF is a critical path activity in most cases. | SA | A | N | D | DK |
| 11 | Performance of many subsequent WFs relies heavily on this WF. | SA | A | N | D | DK |
| 12 | This WF involves a significant amount of data updating. | SA | A | N | D | DK |
| 13 | This WF activity requires spatial coordination. | SA | A | N | D | DK |
| 14 | Management of this WF operates in close proximity to workers. | SA | A | N | D | DK |
| 15 | This WF involves high probability of change. | SA | A | N | D | DK |

Work Function (WF): **Carry out earthwork and grading** (Construction Execution Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves repetitive activity. | SA | A | N | D | DK |
| 2 | This WF involves many individuals with different skills and specialties. | SA | A | N | D | DK |
| 3 | The products of this WF are physically large and bulky. | SA | A | N | D | DK |
| 4 | Errors from this WF are difficult to fix or requires a large amount of resources to fix. | SA | A | N | D | DK |
| 5 | This WF activity requires spatial coordination. | SA | A | N | D | DK |
| 6 | This WF involves relatively high uncertainty in the following. | Quality | Cost | Schedule | Safety | |
| 7 | The management of this WF operates in close proximity to workers. | SA | A | N | D | DK |
| 8 | This WF involves high probability of change. | SA | A | N | D | DK |
| 9 | Some resources of this WF are often idle. | SA | A | N | D | DK |
| 10 | The procedures of this WF are very complex. | SA | A | N | D | DK |
| 11 | User's, worker's, or operator's experience is critical to performance of this WF. | SA | A | N | D | DK |
| 12 | This WF involves environmental hazard. | SA | A | N | D | DK |
| 13 | This WF is costly to execute. | SA | A | N | D | DK |
| 14 | This WF relies on or requires physical output products of many previous WFs. | SA | A | N | D | DK |

Work Function (WF): **Construct bar cages** (Construction Execution Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves repetitive activity. | SA | A | N | D | DK |
| 2 | This WF involves many individuals with different skills and specialties. | SA | A | N | D | DK |
| 3 | The products of this WF are physically large and bulky. | SA | A | N | D | DK |
| 4 | Errors from this WF are difficult to fix or requires a large amount of resources to fix. | SA | A | N | D | DK |
| 5 | This WF activity requires spatial coordination. | SA | A | N | D | DK |
| 6 | This WF involves relatively high uncertainty in the following. | Quality | Cost | Schedule | Safety | |
| 7 | The management of this WF operates in close proximity to workers. | SA | A | N | D | DK |
| 8 | This WF involves high probability of change. | SA | A | N | D | DK |
| 9 | Some resources of this WF are often idle. | SA | A | N | D | DK |
| 10 | The procedures of this WF are very complex. | SA | A | N | D | DK |
| 11 | User's, worker's, or operator's experience is critical to performance of this WF. | SA | A | N | D | DK |
| 12 | This WF involves environmental hazard. | SA | A | N | D | DK |
| 13 | This WF is costly to execute. | SA | A | N | D | DK |
| 14 | This WF relies on or requires physical output products of many previous WFs. | SA | A | N | D | DK |

Work Function (WF): **Manipulate and hang sheet rock** (Construction Execution Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves repetitive activity. | SA | A | N | D | DK |
| 2 | This WF involves many individuals with different skills and specialties. | SA | A | N | D | DK |
| 3 | The products of this WF are physically large and bulky. | SA | A | N | D | DK |
| 4 | Errors from this WF are difficult to fix or requires a large amount of resources to fix. | SA | A | N | D | DK |
| 5 | This WF activity requires spatial coordination. | SA | A | N | D | DK |
| 6 | This WF involves relatively high uncertainty in the following. | Quality | Cost | Schedule | Safety | |
| 7 | The management of this WF operates in close proximity to workers. | SA | A | N | D | DK |
| 8 | This WF involves high probability of change. | SA | A | N | D | DK |
| 9 | Some resources of this WF are often idle. | SA | A | N | D | DK |
| 10 | The procedures of this WF are very complex. | SA | A | N | D | DK |
| 11 | User's, worker's, or operator's experience is critical to performance of this WF. | SA | A | N | D | DK |
| 12 | This WF involves environmental hazard. | SA | A | N | D | DK |
| 13 | This WF is costly to execute. | SA | A | N | D | DK |
| 14 | This WF relies on or requires physical output products of many previous WFs. | SA | A | N | D | DK |

Work Function (WF): **Apply paint or coating** (Construction Execution Phase)

| ID | Work Function Characteristic (WFC) | Assessment of WFC to WF | | | | |
|---|---|---|---|---|---|---|
| 1 | This WF involves repetitive activity. | SA | A | N | D | DK |
| 2 | This WF involves many individuals with different skills and specialties. | SA | A | N | D | DK |
| 3 | The products of this WF are physically large and bulky. | SA | A | N | D | DK |
| 4 | Errors from this WF are difficult to fix or requires a large amount of resources to fix. | SA | A | N | D | DK |
| 5 | This WF activity requires spatial coordination. | SA | A | N | D | DK |
| 6 | This WF involves relatively high uncertainty in the following. | Quality | Cost | Schedule | Safety | |
| 7 | The management of this WF operates in close proximity to workers. | SA | A | N | D | DK |
| 8 | This WF involves high probability of change. | SA | A | N | D | DK |
| 9 | Some resources of this WF are often idle. | SA | A | N | D | DK |
| 10 | The procedures of this WF are very complex. | SA | A | N | D | DK |
| 11 | User's, worker's, or operator's experience is critical to performance of this WF. | SA | A | N | D | DK |
| 12 | This WF involves environmental hazard. | SA | A | N | D | DK |
| 13 | This WF is costly to execute. | SA | A | N | D | DK |
| 14 | This WF relies on or requires physical output products of many previous WFs. | SA | A | N | D | DK |

# APPENDIX C-1

## Raw Datat Set from the Survey of Assessment of the Linkage between Work Function Characteristics and Technology Demand

| ID for survey | Participants | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 |
| 1 | 1 | 4 | 3 | 3 | 3 | 4 | 3 | 3 |
| 2 | 3 | 4 | 4 | 3 | 3 | 4 | 3 | 4 |
| 3 | 4 | 4 | 2 | 4 | 3 | 4 | 4 | 4 |
| 4 | 2 | 3 | 3 | 3 | 4 | 3 | 3 | 4 |
| 5 | 1 | 3 | 3 | 4 | 2 | 4 | 3 | 3 |
| 6 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 2 |
| 7 | 3 | 4 | 3 | 3 | 3 | 4 | 1 | 4 |
| 8 | 4 | 4 | 3 | 2 | 2 | 2 | 1 | 4 |
| 9 | 3 | 4 | 2 | 4 | 2 | 3 | 4 | 4 |
| 10 | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 |
| 11 | 4 | 2 | 2 | 3 | 4 | 3 | 3 | 4 |
| 12-1 | 3 | 4 | 3 | 3 | 2 | 2 | 3 | 2 |
| 12-2 | 4 | 4 | 3 | 3 | 3 | 2 | 3 | 4 |
| 12-3 | 4 | 4 | 3 | 3 | 4 | 2 | 2 | 4 |
| 12-4 | 3 | 2 | 3 | 3 | 1 | 2 | 3 | 3 |
| 13 | 2 | 3 | 2 | 3 | 2 | 4 | 3 | 3 |
| 14 | 1 | 3 | 3 | 4 | 2 | 3 | 2 | 4 |
| 15 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 15 | 2 | 4 | 4 | 3 | 3 | 2 | 3 | 2 |
| 17 | 4 | 4 | 2 | 4 | 3 | 4 | 4 | 3 |
| 18 | 3 | 4 | 4 | 4 | 3 | 4 | 3 | 3 |
| 19 | 2 | 3 | 4 | 3 | 3 | 2 | 2 | 2 |
| 20 | 4 | 2 | 2 | 1 | DK | 2 | 3 | 2 |
| 21 | 2 | 3 | 3 | 3 | 2 | 2 | 3 | 4 |
| 22 | 4 | 4 | 3 | 4 | 2 | 2 | 3 | 4 |
| 23-1 | 2 | 3 | 2 | 3 | 3 | 2.5 | 3 | 3 |
| 23-2 | 2 | 3 | 3 | 3 | 3 | 2.5 | 3 | 3 |
| 23-3 | 2 | 2 | 3 | 3 | 4 | 2.5 | 3 | 3 |
| 23-4 | 2 | 2 | 2 | 3 | 1 | 2.5 | 3 | 4 |
| 24 | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 1 |
| 25 | 1 | 3 | 3 | 3 | 3 | 3 | 1 | 4 |
| 26 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 3 |
| 27 | 2 | 2 | 4 | 4 | 3 | 2 | 3 | 4 |
| 28 | 3 | 2 | 4 | 2 | 3 | 2 | 2 | 3 |
| 29 | 4 | 2 | 3 | 2 | 1 | 2 | 3 | 3 |
| 30 | 4 | 3 | 3 | 3 | 3 | 2 | 3 | 3 |
| 31 | 2 | 3 | 4 | 3 | 1 | 2 | 3 | 2 |

# APPENDIX C-2

## RAW DATAT SET FROM THE SURVEY OF CHARACTERIZING WORK FUNCTIONS - FOR OWNER-RESPONSIBLE WORK FUNCTIONS

**WF: Develop a milestone schedule from the scope of work (Front End Phase)**

| ID | Participants | | | | | | |
|---|---|---|---|---|---|---|---|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 |
| 1 | 3 | 3 | 3 | 4 | 3 | 3 | 4 |
| 2 | 4 | 3 | 3 | 4 | 2 | 3 | 4 |
| 3 | 3 | 4 | 3 | 3 | 1 | 3 | 3 |
| 4 | 1-2 | 3-5 | 3-5 | 3-5 | 3-5 | 3-5 | 6 or more |
| 5 | 3 | 4 | 1 | 3 | 3 | 2 | 1 |
| 6 | 1 | 3 | 1 | 1 | 3 | 3 | 2 |
| 7 | 2 | 3 | 1 | 3 | 1 | 2 | 3 |
| 8 | 1 | 3 | 2 | 4 | 1 | 3 | 3 |

**WF: Determine the lead time required to order equipment and materials (Procurement Phase)**

| ID | Participants | | | | | | |
|---|---|---|---|---|---|---|---|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 |
| 1 | 1 | 3 | 2 | 3 | 2 | 3 | 2 |
| 2 | 3 | 3 | 2 | 4 | 3 | 2 | 3 |
| 3 | 4 | 4 | | 4 | 2 | 3 | 4 |
| 4 | 2-5 | 2-5 | 2-5 | 6 or more | 2-5 | 2-5 | 2-5 |
| 5 | 2 | 3 | 3 | 3 | 3 | 2 | 3 |
| 6 | 1 | 3 | 2 | 3 | 2 | 2 | 2 |
| 7 | 3 | 4 | 3 | 4 | 4 | 3 | 3 |
| 8 | DK | 2 | 3 or more | 3 or more | 3 or more | 2 | 3 or more |
| 9 | Schedule | Schedule | Schedule | Cost | Schedule | Schedule | Schedule |
| 10 | 3 | 4 | 3 | 4 | 3 | 3 | 3 |
| 11 | 2 | 3 | 1 | 3 | 3 | 3 | 1 |
| 12 | 3 | 3 | 2 | 3 | 3 | 1 | 1 |
| 13 | 4 | 3 | 3 | 4 | 4 | 3 | 4 |
| 14 | 4 | 3 | 3 | 4 | 4 | 3 | 3 |
| 15 | 3 | 3 | 1 | 3 | 3 | 2 | 2 |
| 16 | Cost | Schedule | Schedule | Quality | Schedule | Qual/Sche | Schedule |

| **WF: Use as-built information in personnel training (Operation and Maintenance Phase)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| ID | Participants | | | | | | |
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 |
| 1 | DK | 1-2 | 6 or more | 6 or more | 3-5 | 1-2 | 6 or more |
| 2 | DK | 3 | 3 | 1 | 3 | 3 | 4 |
| 3 | DK | 1 | 3 | 1 | 2 | 2 | 1 |
| 4 | 3 | 3 | 3 | 4 | 4 | 3 | 3 |
| 5 | 3 | 3 | 3 | 1 | 2 | 2 | 2 |
| 6 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 7 | DK | 1 | 2 | 1 | 3 | 2 | 1 |
| 8 | DK | 1 | 2 | 4 | 1 | 2 | 1 |
| 9 | 3 | 3 | 2 | 3 | 1 | 2 | 2 |
| 10 | DK | 1 | 2 | 4 | 2 | 2 | 3 |
| 11 | 3 | 3 | 3 | 4 | 3 | 4 | 4 |
| 12 | DK | 1 | 2 | 3 | 1 | 2 | 2 |
| 13 | 3 | 3 | 2 | 3 | 1 | 1 | 2 |
| 14 | 2 | 3 | 3 | 1 | 3 | 2 | 3 |

# APPENDIX C-3

## RAW DATAT SET FROM THE SURVEY OF CHARACTERIZING WORK FUNCTIONS - FOR A/E-RESPONSIBLE WORK FUNCTIONS

| WF: Get input from builders and suppliers regarding construction methods selection and sequence (Design Phase) | | | | |
|---|---|---|---|---|
| ID | Participants | | | |
| | #1 | #2 | #3 | #4 |
| 1 | 2 | 3 | 4 | 4 |
| 2 | 3 | 3 | 3 | 2 |
| 3 | 2 | 2 | 2 | 3 |
| 4 | 3 | 1 | 3 | 1 |
| 5 | 2 | 2 | 4 | 4 |
| 6 | 2 | 3 | 4 | 2 |
| 7 | 1 | 3 | 3 | 2 |
| 8 | 3 more | DK | 3 more | 3 more |
| 9 | Schedule | Cost | Schedule | Quality |
| 10 | 4 | 3 | 4 | 4 |
| 11 | 3 | 4 | 4 | 1 |
| 12 | 4 | 2 | 1 | 3 |
| 13 | 4 | 2 | 4 | 2 |

| WF: Design the structural systems and related drawings (Design Phase) | | | | |
|---|---|---|---|---|
| ID | Participants | | | |
| | #1 | #2 | #3 | #4 |
| 1 | 3 | 4 | 4 | 3 |
| 2 | 1 | 2 | 4 | 3 |
| 3 | 3 | 3 | 4 | 3 |
| 4 | 4 | 1 | 3 | 2 |
| 5 | DK | 2 | 3 | 1 |
| 6 | 2 | 2 | 2 | 1 |
| 7 | 4 | 4 | 4 | 3 |
| 8 | 1 | 2 | 3 or more | 1 |
| 9 | Safety | Quality | Quality | Safety |
| 10 | 3 | 3 | 4 | 3 |
| 11 | 4 | 4 | 4 | 1 |
| 12 | 4 | 2 | 1 | 1 |
| 13 | 2 | 2 | 4 | 2 |

| WF: Generate facility floor plans (Design Phase) | | | | |
|---|---|---|---|---|
| ID | Participants | | | |
| | #1 | #2 | #3 | #4 |
| 1 | 4 | 4 | 4 | 3 |
| 2 | 1 | 3 | 4 | 2 |
| 3 | 2 | 3 | 3 | 2 |
| 4 | 3 | 3 | 3 | 1 |
| 5 | 2 | 2 | 4 | 1 |
| 6 | 3 | 2 | 4 | 1 |
| 7 | 3 | 3 | 4 | 2 |
| 8 | 3 more | 3 or more | 3 or more | 1 |
| 9 | Quality | Quality | Quality | Quality |
| 10 | 4 | 4 | 4 | 3 |
| 11 | 4 | 4 | 4 | 1 |
| 12 | 4 | 3 | 1 | 1 |
| 13 | 3 | 3 | 4 | 2 |

# APPENDIX C-4

## RAW DATAT SET FROM THE SURVEY OF CHARACTERIZING WORK FUNCTIONS - FOR GC-RESPONSIBLE WORK FUNCTIONS

| **WF: Determine the lead time required to order equipment and materials (Procurement Phase)** | | | | | | |
|---|---|---|---|---|---|---|
| ID | Participants | | | | | |
| | #1 | #2 | #3 | #4 | #5 | #6 |
| 1 | 1 | 4 | 2 | 3 | 3 | 2 |
| 2 | 4 | 3 | 3 | 3 | 3 | 2 |
| 3 | 1 | 3 | 2 | 4 | 2 | 1 |
| 4 | 6 or more | 2-5 | 2-5 | 2-5 | 1 | 2-5 |
| 5 | 3 | 1 | 1 | 3 | 3 | 2 |
| 6 | 3 | 3 | 2 | 3 | 3 | 1 |
| 7 | 4 | 3 | 4 | 3 | 2 | 3 |
| 8 | 3 or more | 3 or more | 3 or more | 3 or more | 3 or more | 2 |
| 9 | Quality | Schedule | Schedule | Schedule | Schedule | Schedule |
| 10 | 4 | 3 | 4 | 4 | 3 | 3 |
| 11 | 1 | 1 | 2 | 2 | 1 | 1 |
| 12 | 3 | 1 | 1 | 3 | 2 | 1 |
| 13 | 4 | 3 | 4 | 4 | 4 | 1 |
| 14 | 4 | 3 | 4 | 4 | 3 | 2 |
| 15 | 4 | 3 | 2 | 3 | 1 | 1 |
| 16 | Schedule | Schedule | Schedule | Schedule | Schedule | Safety |

| WF: Track the inventory of materials on site (Construction Management Phase) | | | | | | |
|---|---|---|---|---|---|---|
| ID | Participants | | | | | |
| | #1 | #2 | #3 | #4 | #5 | #6 |
| 1 | 3 | 3 | 3 | 4 | 2 | 2 |
| 2 | 3 | 2 | 3 | 3 | 2 | 2 |
| 3 | 3 | 2 | 3 | 3 | 1 | 2 |
| 4 | 4 | 3 | 3 | 4 | 3 | 2 |
| 5 | 3 or more | 3 or more | 2 | 2 | DK | 1 |
| 6 | Quality | Schedule | Cost/Schd | Schedule | Schedule | Schedule |
| 7 | 4 | 3 | 3 | 4 | 4 | 3 |
| 8 | 1 | 1 | 1 | 3 | 2 | 1 |
| 9 | 1 | 1 | 1 | 2 | 1 | 1 |
| 10 | 1 | 3 | 2 | 3 | 1 | 1 |
| 11 | 4 | 3 | 3 | 4 | 2 | 1 |
| 12 | 4 | 3 | 3 | 4 | 3 | 3 |
| 13 | 4 | 1 | 3 | 3 | 1 | 2 |
| 14 | 4 | 1 | 3 | 3 | 1 | 2 |
| 15 | 4 | 3 | 3 | 3 | 2 | 2 |

| WF: Update the current cost forecast (Construction Management Phase) | | | | | | |
|---|---|---|---|---|---|---|
| ID | Participants | | | | | |
| | #1 | #2 | #3 | #4 | #5 | #6 |
| 1 | 4 | 4 | 4 | 4 | 3 | 2 |
| 2 | 3 | 3 | 2 | 3 | 1 | 2 |
| 3 | 3 | 2 | 3 | 3 | 1 | 2 |
| 4 | 3 | 4 | 4 | 4 | 3 | 3 |
| 5 | 3 or more | 3 or more | 1 | 3 or more | 2 | 1 |
| 6 | Cost | Cost | Cost | Cost | Cost | Cost |
| 7 | 4 | 4 | 4 | 4 | 2 | 3 |
| 8 | 4 | 4 | 4 | 4 | 3 | 2 |
| 9 | 1 | 1 | 2 | 2 | 1 | 1 |
| 10 | 1 | 1 | 3 | 2 | 1 | 1 |
| 11 | 3 | 2 | 3 | 3 | 1 | 1 |
| 12 | 4 | 4 | 4 | 4 | 2 | 2 |
| 13 | 1 | 1 | 3 | 2 | 1 | 1 |
| 14 | 1 | 1 | 2 | 2 | 1 | 1 |
| 15 | 3 | 4 | 3 | 4 | 1 | 2 |

| **WF: Carry out earthwork and grading (Construction Execution Phase)** | | | | | | |
|---|---|---|---|---|---|---|
| ID | Participants | | | | | |
| | #1 | #2 | #3 | #4 | #5 | #6 |
| 1 | 3 | 3 | 2 | 4 | 1 | 2 |
| 2 | 2 | 2 | 2 | 3 | 3 | 3 |
| 3 | 3 | 4 | 3 | 4 | 3 | 3 |
| 4 | 4 | 3 | 2 | 3 | 3 | 1 |
| 5 | 4 | 4 | 3 | 3 | 3 | DK |
| 6 | Schedule | Cost/Schd | Quality | Quality | Quality | Quality |
| 7 | 4 | 3 | 3 | 4 | 3 | 2 |
| 8 | 1 | 2 | 1 | 3 | 2 | 2 |
| 9 | 3 | 3 | 2 | 2 | 3 | 1 |
| 10 | 3 | 1 | 1 | 2 | 2 | 1 |
| 11 | 4 | 3 | 3 | 4 | 3 | 4 |
| 12 | 3 | 2 | 1 | 3 | 2 | 2 |
| 13 | 4 | 3 | 1 | 3 | 1 | 2 |
| 14 | 3 | 2 | 1 | 3 | 2 | 1 |

| **WF: Construct rebar cages (Construction Execution Phase)** | | | | | | |
|---|---|---|---|---|---|---|
| ID | Participants | | | | | |
| | #1 | #2 | #3 | #4 | #5 | #6 |
| 1 | 3 | 3 | 3 | 4 | 3 | 2 |
| 2 | 1 | 1 | 1 | 3 | 2 | 1 |
| 3 | 3 | 3 | 3 | 3 | 3 | 2 |
| 4 | 2 | 1 | 1 | 2 | 2 | 1 |
| 5 | 3 | 3 | 1 | 3 | 1 | DK |
| 6 | Quality | Qual/Cost | Safe | Quality | Schedule | Quality |
| 7 | 4 | 3 | 3 | 4 | 3 | 2 |
| 8 | 1 | 1 | 1 | 3 | 2 | 2 |
| 9 | 2 | 1 | 2 | 3 | 1 | 2 |
| 10 | 1 | 2 | 1 | 1 | 2 | 1 |
| 11 | 3 | 2 | 2 | 4 | 1 | 4 |
| 12 | 1 | 1 | 1 | 2 | 1 | 1 |
| 13 | 2 | 2 | 1 | 2 | 2 | 2 |
| 14 | 2 | 2 | 1 | 3 | 1 | 1 |

| WF: Manipulate and hang sheet rock (Construction Execution) | | | | | | |
|---|---|---|---|---|---|---|
| ID | Participants | | | | | |
| | #1 | #2 | #3 | #4 | #5 | #6 |
| 1 | 3 | 4 | 3 | 4 | 3 | DK |
| 2 | 1 | 1 | 2 | 2 | 3 | DK |
| 3 | 2 | 3 | 3 | 3 | 3 | DK |
| 4 | 2 | 1 | 3 | 3 | 1 | DK |
| 5 | 3 | 3 | 3 | 3 | 1 | DK |
| 6 | Quality | Quality | Quality | Quality | Quality | DK |
| 7 | 3 | 3 | 3 | 4 | 2 | DK |
| 8 | 1 | 2 | 2 | 2 | 1 | DK |
| 9 | 1 | 1 | 2 | 3 | 2 | DK |
| 10 | 1 | 1 | 1 | 1 | 1 | DK |
| 11 | 4 | 3 | 3 | 3 | 3 | DK |
| 12 | 1 | 1 | 1 | 2 | 1 | DK |
| 13 | 2 | 2 | 3 | 2 | 1 | DK |
| 14 | 1 | 3 | 2 | 3 | 1 | DK |

| WF: Apply paint or coating (Construction Execution) | | | | | | |
|---|---|---|---|---|---|---|
| ID | Participants | | | | | |
| | #1 | #2 | #3 | #4 | #5 | #6 |
| 1 | 3 | 3 | 3 | 4 | 3 | DK |
| 2 | 1 | 1 | 1 | 3 | 3 | DK |
| 3 | 1 | 1 | 1 | 2 | 1 | DK |
| 4 | 1 | 1 | 1 | 4 | 1 | DK |
| 5 | 3 | 2 | 3 | 3 | 1 | DK |
| 6 | Quality | Quality | Quality | Quality | Quality | DK |
| 7 | 3 | 3 | 3 | 4 | 3 | DK |
| 8 | 1 | 2 | 2 | 3 | 1 | DK |
| 9 | 1 | 1 | 1 | 2 | 2 | DK |
| 10 | DK | 1 | 1 | 2 | 1 | DK |
| 11 | 4 | 3 | 3 | 4 | 2 | DK |
| 12 | 3 | 2 | 3 | 4 | 3 | DK |
| 13 | 1 | 1 | 1 | 2 | 2 | DK |
| 14 | 1 | 3 | 3 | 3 | 2 | DK |

# APPENDIX D

## Raw Datat Set from the Survey of Application Model

| WF: Conduct market analysis or need analysis for a new facility | | | |
|---|---|---|---|
| ID | Participants | | |
| | #1 | #2 | #3 |
| 1 | 4 | 4 | 4 |
| 2 | 3 | 4 | 4 |
| 3 | 4 | 4 | 4 |
| 4 | 3-5 | DK | 1-2 |
| 5 | 1 | 3 | 1 |
| 6 | 3 | 3 | 3 |
| 7 | 3 | 3 | 3 |
| 8 | 3 | 3 | 4 |

| WF: Check the design against owner requirements and code requirements | | | |
|---|---|---|---|
| ID | Participants | | |
| | #1 | #2 | #3 |
| 1 | 3 | 4 | 3 |
| 2 | 2 | 2 | 3 |
| 3 | 4 | 3 | 3 |
| 4 | 3 | DK | 3 |
| 5 | 4 | 3 | 3 |
| 6 | 4 | 4 | 3 |
| 7 | 3 | 4 | 3 |
| 8 | 3 or more | 2-3 | 2 |
| 9 | Quality | Cost | Quality |
| 10 | 3 | 4 | 3 |
| 11 | 4 | 4 | 3 |
| 12 | 2 | 1 | 2 |
| 13 | 3 | 4 | 2 |

| **WF: Monitor the progress of fabricator** | | | |
|---|---|---|---|
| ID | Participants | | |
| | #1 | #2 | #3 |
| 1 | 2 | DK | 1 |
| 2 | 4 | 3 | 1 |
| 3 | 2 | 3 | 3 |
| 4 | 2-5 | 6 or more | 2-5 |
| 5 | 3 | 3 | 3 |
| 6 | 2 | 4 | 3 |
| 7 | 3 | 4 | 2 |
| 8 | 2 | 3 or more | 2 |
| 9 | Schedule | Quality | Schedule |
| 10 | 4 | 4 | 3 |
| 11 | 2 | 4 | 2 |
| 12 | 1 | 4 | 1 |
| 13 | 1 | 3 | 3 |
| 14 | 3 | 4 | 3 |
| 15 | | 4 | 3 |
| 16 | Schedule | Cost | Schedule |

| **WF: Plan the transportation routes of large items from the fabricator to the job site** | | | |
|---|---|---|---|
| ID | Participants | | |
| | #1 | #2 | #3 |
| 1 | 3 | 3 | 2 |
| 2 | 2 | 3 | 3 |
| 3 | 3 | 3 | 2 |
| 4 | 2-5 | DK | 2-5 |
| 5 | 4 | DK | 3 |
| 6 | 3 | 4 | 2 |
| 7 | 3 | 4 | 3 |
| 8 | 2 | 3 or more | 3 or more |
| 9 | Schedule | Sch. Safe | Schedule |
| 10 | 3 | 4 | 3 |
| 11 | 2 | 4 | 2 |
| 12 | 3 | 4 | 3 |
| 13 | 1 | 4 | 3 |
| 14 | 3 | 4 | 3 |
| 15 | 2 | 1 | 3 |
| 16 | Schedule | Schedule | Schedule |

| **WF: Maintain daily job diary** | | | |
|---|---|---|---|
| | Participants | | |
| | #1 | #2 | #3 |
| 1 | 4 | DK | 3 |
| 2 | 4 | 4 | 3 |
| 3 | 4 | 4 | 3 |
| 4 | 2 | 4 | 2 |
| 5 | 1 | 3 or more | 1 |
| 6 | DK | Cost | Quality |
| 7 | 3 | 4 | 2 |
| 8 | 1 | 4 | 2 |
| 9 | 1 | DK | 3 |
| 10 | 1 | DK | 2 |
| 11 | 1 | DK | 1 |
| 12 | 4 | 4 | 3 |
| 13 | 3 | DK | 1 |
| 14 | 3 | 3 | 1 |
| 15 | 3 | DK | 1 |

| **WF: Link field material manager to suppliers** | | | |
|---|---|---|---|
| | Participants | | |
| | #1 | #2 | #3 |
| 1 | 3 | 4 | 3 |
| 2 | 4 | 3 | 3 |
| 3 | 4 | 4 | 3 |
| 4 | 4 | 4 | 4 |
| 5 | 3 or more | 3 or more | 3 or more |
| 6 | Quality | Quality | Schedule |
| 7 | 4 | 4 | 4 |
| 8 | 2 | 4 | 3 |
| 9 | 1 | DK | 3 |
| 10 | 1 | 3 | 1 |
| 11 | 3 | 4 | N/A |
| 12 | 3 | 4 | 4 |
| 13 | 4 | DK | 1 |
| 14 | 3 | 3 | 1 |
| 15 | 3 | 3 | 4 |

| WF: Communicate design changes to field personnel | | | |
|---|---|---|---|
| ID | Participants | | |
| | #1 | #2 | #3 |
| 1 | 3 | 4 | 4 |
| 2 | 4 | 4 | 4 |
| 3 | 4 | 4 | 4 |
| 4 | 3 | 4 | 4 |
| 5 | 2 | 2 | 3 or more |
| 6 | Quality | Schedule | Cost/Sche. |
| 7 | 4 | 4 | 4 |
| 8 | 1 | 4 | 2 |
| 9 | 1 | DK | 1 |
| 10 | 4 | 3 | 4 |
| 11 | 4 | 4 | 4 |
| 12 | 3 | 4 | 4 |
| 13 | 4 | 3 | 3 |
| 14 | 3 | 4 | 1 |
| 15 | 4 | 4 | 3 |

| WF: Communicate RFI and response | | | |
|---|---|---|---|
| ID | Participants | | |
| | #1 | #2 | #3 |
| 1 | 4 | 4 | 4 |
| 2 | 4 | 4 | 4 |
| 3 | 3 | 4 | 4 |
| 4 | 3 | 4 | 4 |
| 5 | 3 or more | 3 or more | 3 or more |
| 6 | Quality | Schedule | Schedule |
| 7 | 4 | 4 | 4 |
| 8 | 1 | 3 | 3 |
| 9 | 1 | 2 | 1 |
| 10 | 3 | 4 | 4 |
| 11 | 4 | 4 | 4 |
| 12 | 4 | 4 | 4 |
| 13 | 3 | 1 | 1 |
| 14 | 3 | 2 | 1 |
| 15 | 3 | 4 | 4 |

| WF: Weld pipes | | | |
|---|---|---|---|
| | Participants | | |
| | #1 | #2 | #3 |
| 1 | 4 | 3 | 4 |
| 2 | 2 | 2 | 1 |
| 3 | 4 | 4 | 3 |
| 4 | 4 | 4 | 3 |
| 5 | 4 | 4 | 3 |
| 6 | Quality | DK | Cost |
| 7 | 2 | 4 | 3 |
| 8 | 2 | DK | 3 |
| 9 | 3 | DK | 4 |
| 10 | 4 | 3 | 1 |
| 11 | 4 | 4 | 4 |
| 12 | 3 | 4 | 4 |
| 13 | 3 | DK | 4 |
| 14 | 4 | 3 | 4 |

| WF: Update as-built drawings | | | |
|---|---|---|---|
| | Participants | | |
| | #1 | #2 | #3 |
| 1 | **3-5** | 1-2 | 6 or more |
| 2 | 4 | 3 | 3 |
| 3 | 4 | 2 | 4 |
| 4 | 4 | 4 | 3 |
| 5 | 3 | 4 | 3 |
| 6 | 3 | 1 | 3 |
| 7 | 1 | 3 | 1 |
| 8 | 3 | 3 | 1 |
| 9 | 2 | DK | 1 |
| 10 | 2 | 3 | 1 |
| 11 | 2 | 4 | 3 |
| 12 | 1 | DK | 1 |
| 13 | 2 | 3 | 1 |
| 14 | 4 | 4 | 3 |

# APPENDIX E

## LITERATURE SURVEY RESULTS OF TECHNOLOGY SUPPLY - 12 WORK FUNCTIONS FOR THE RESEARCH PROOF MODEL

| Owner (Front-End) | Owner | Front-End | A/E (Design) | GC (Procurement) |
|---|---|---|---|---|
| Project Management | **WF1.05: Develop a milestone schedule from the scope of work** | | Contract Documentation | Scheduling |

| | | |
|---|---|---|
| **Tools** | Project Management Software<br>Web-based Project Management System | |
| | | Primavera Project Planner<br>Microsoft Project<br>TimeControl<br>Spreadsheet application |
| **Base Technologies** | Internet<br>Network | Database |
| **Standard Interfaces** | | Open Database Connectivity (ODBC) |

| A/E | Design |
| --- | --- |
| **WF 2.01: Get input from builders and suppliers regarding construction methods selection and sequence** | |

Suppliers
GC

| | |
| --- | --- |
| **Tools** | Documentation with a function of search and update<br>In-house Database system<br>Knowledge management system<br>Communication tools: e-mail, fax, website<br>Decision analysis tools: @RISK, Decision Pro |
| **Base Technologies** | Virtual Reality<br>Simulation |
| **Standard Interfaces** | |

| | A/E | Design | A/E, GC (Procurement) | GC (Construction Management) |
|---|---|---|---|---|
| | **WF2.05: Generate floor plans** | | | |
| **Tools** | Full CAD Software<br>AutoCAD Series, Microstation Series, TurboCAD, PowerCAD, IntelliCAD, DenebaCAD<br>CADKEY, GDS, FastCAD, Vdraft, DynaCAD, FelixCAD<br><br>Architectural CADD<br>AllPlan, ARC+, ArchiCAD, ArchiTECH.PC, Architrion, ARRIS, DataCAD, Project Architech, Cadvance, Caddsman Architect, SoftPlan, BuildersCAD, SolidBuilder, ChiefArchitect<br><br>Software for home building<br>Fast Plans 7<br>Home Plan Pro<br>FloorPan | | | |
| **Base Technologies** | Object-Oriented CAD Model<br>3-D CAD | | | |
| **Standard Interfaces** | Import & export data file | | Link to quantity take-off | Link to cost and schedule control |

| | A/E (Design) | A/E | | Design | | A/E (Design) |
|---|---|---|---|---|---|---|
| | | **WF2.07: Design the structural systems and related drawings** | | | | |
| | Preliminary design | Mathematical model representation | Numerical calculation | Code check (Specification) | Structure detailing | CAD detailing |
| **Tools** | | ANSYS | | NISA-Civil<br>In-house software | | |
| | | Display IV<br>PATRAN<br>I-DEAS | GT STRUDL<br>NASTRAN<br>ABAQUS<br>ADINA<br>ALGOR-Civil<br>NISA II | | | |
| | | | SAP 2000, ETABS, SAFE<br>LUSAS<br>STAAD<br>STRAND 7 | | | |
| | | | | DESCON<br>CDS | | |
| **Base Technologies** | Expert system | | FEM<br>Numerical Analysis | | | |
| **Standard Interfaces** | | Import & export data file | | | | |

| Owner, GC | Procurement |
|---|---|
| **WF 3.01: Determine the lead time required to order equipment and materials** | |

| Owner, GC | Suppliers |
|---|---|
| Scheduling | Procurement |

| | |
|---|---|
| **Tools** | In-house Database System<br>Communication tools with suppliers and vendors<br>ERP |
| **Base Technologies** | Internet for B2B |
| **Standard Interfaces** | XML |

| | | | |
|---|---|---|---|
| GC<br>(Project<br>Management) | Payroll, Purchase Order<br>Change Order, Invoice<br>Cost Estimating<br>Job Cost | | GC<br>(Construction<br>Management) |
| Project<br>Administration<br>Field<br>Administration | **GC** | **Construction Management** | Scheduling |
| | **WF4.04: Update the current cost forecast** | | |

| | |
|---|---|
| **Tools** | BSD CostLink, BuildSoft, Computerease, CostTrack, Forefront by Dexter & Chaney, Foundation for Windows, MasterBuilder by Omware, Newstar, NGS 2000 by Maxwell Systems, Profitbuilder Millenium, ProjectTacker, Prolog Manager 6, Sirius, Solomon IV<br>Starbuilder from GEAC, The Construction Manager, Timberline Extended and Standard, Viewpoint by Bidtek, Winjob by Deneb |
| **Base Technologies** | Database |
| **Standard Interfaces** | ODBC |

| | A/E (Design) | **GC** / **Construction Management**<br>**WF4.06: Track the inventory of materials on site**<br>Order / Receive / Inspect / Store / Issue | GC (Construction Management) | Supplier (Procurement) |
|---|---|---|---|---|
| **Tools** | CAD | Tool tracking and management system (Tool/Watch)<br>Software managing tools, equipment, and supplies (Tracker 7) | Accounting system | |
| **Base Technologies** | | Bar code, 2D bar code<br>Database<br>Radio Frequency Tag | | |
| **Standard Interfaces** | Interface from CAD | Interface with database from input device | | Standard bar code |

| | A/E (Design) | GC | | | Construction Execution | |
|---|---|---|---|---|---|---|
| | | **WF5.02: Carry out earthwork and grading** | | | | |
| | | Excavation | Move | Fill (Backfill) | Grade | Haul |
| **Tools** | | Excavator<br>Excavator loader<br>Excavator with GPS | Dozer<br>Loader<br>Excavator loader<br>Shovel<br>Crane<br>Scraper | Loader<br>Excavator loader<br>Shovel | Grader<br>Compactor<br>Loader<br>Excavator loader<br>Scraper | Truck |
| **Base Technologies** | | GPS | | | Laser grading | |
| **Standard Interfaces** | | | | | | |

<table>
<tr><th></th><th>A/E (Design)</th><th colspan="2">GC</th><th colspan="2">Construction</th></tr>
<tr><th></th><th></th><th colspan="4">WF5.03: Construct rebar cages</th></tr>
<tr><th></th><th>Rebar detailing</th><th>Bending</th><th>Shearing</th><th>Tying</th><th>Placing</th></tr>
<tr><td rowspan="3">Tools</td><td>GEOPAK<br>IntelCAD-RC</td><td>PG Benders (GENSCO)<br>STEMA(stirrup bender)<br><br>Rebar bending robot from Obayashi Corp.</td><td>Yard Shears (GENSCO)</td><td rowspan="2">Automatic tying machine</td><td rowspan="3">Automatic rebar placing robot (Japan)</td></tr>
<tr><td rowspan="2"></td><td colspan="2">Carell Combo (Ocean Machinery)<br>NC RCB machine</td></tr>
<tr><td colspan="3">Rebar pre-assemble robot from Shimizu Corp.<br>Automatic fabrication of unit rebar from Takenaka Corp.<br>Reinforcing bar fabricating robot from Taisei Corp.</td></tr>
<tr><td>Base Technologies</td><td>RCCS</td><td>Neural Network</td><td></td><td></td><td>Robotic assembly for beams and columns</td></tr>
<tr><td>Standard Interfaces</td><td colspan="3">Interface with CAD</td><td></td><td></td></tr>
</table>

| | **GC** | | **Construction** | | | GC (Construction) |
|---|---|---|---|---|---|---|
| | **WF5.08: Hang and manipulate sheetrock** | | | | | |
| | Cutting | Hanging or attaching | Taping & Floating | Filling | Joint finishing | Painting |
| **Tools** | Utility knife, Router | Pneumatic nailing equipment, Electric or pneumatic screw gun, Staple<br>Panel lift<br><br>*Mighty hand from Kajima Corp.*<br>*Sky Hand from Komatsu*<br>*Balance Hand form Komatsu*<br>*Material handling machine from Obayashi Corp.*<br>*Ceiling board installation robot from Kumagai, Shimizu, and Tokyo Construction.* | Clean knife | | Joint knife | |
| **Base Technologies** | | | | | | |
| **Standard Interfaces** | | | | | | |

| | GC | | Construction Execution | |
|---|---|---|---|---|
| | **WF5.11: Apply painting or coating** | | | |
| | Surface preparation | Primer coat, undercoat | Finishing | Inspect & Maintenance |
| **Tools** | Abrasive blasting machinery<br><br>Robotic Bridge Paint Removal System from NCSU | Brush<br>Roller<br>Pump (pneumatic, extrusion, electronic)<br>Airless spray gun<br>Air dryer<br><br>*Automated Surface Finishing System*<br>*Paint spray robot from Fujita Corp.*<br>*Paint coating machine from Fujita Corp.*<br>*Paint spray robot from Kajima Corp.*<br>*KFR-2 from Kumagai Gumi*<br>*SB Multi Coater from Shimizu Corp.*<br>*OSR-1 from Shimizu Corp.*<br>*Paint spray robot from Taisei Corp.*<br>*Wall painting robot from Tokyo Const.* | | |
| **Base Technologies** | | | | |
| **Standard Interfaces** | | | | |

| | GC (Construction) | **Owner** — **Operation and Maintenance**<br>**WF6.03: Use as-built information in personnel training** |
|---|---|---|
| **Tools** | CAD | Manual<br>Computer-based Interactive Training System |
| **Base Technologies** | | Virtual Reality<br>Real-time Visualization<br>Simulation |
| **Standard Interfaces** | | |

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